⟨NBS⟩

Technical Note 262

ACCURACY IN MEASUREMENTS
AND CALIBRATIONS, 1965

EDITED BY
W. A. WILDHACK, R. C. POWELL, AND H. L. MASON

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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Technical Note 262

ISSUED JUNE 15, 1965

ACCURACY IN MEASUREMENTS

AND CALIBRATIONS, 1965

Edited by
W. A. Wildhack, R. C. Powell, and H. L. Mason
NBS Institute for Basic Standards

Abstract

NBS estimates of uncertainties associated with physical measurements, and with some NBS calibration services, are shown by 66 provisional "accuracy charts." Each chart is accompanied by a facing page giving a brief statement of the state of the art and tentative plans for NBS work in areas where improvement is needed.

Foreword

This collection of accuracy charts provides a graphic perspective on the ranges and NBS estimates of uncertainty for measurements or calibrations of many of the physical quantities of importance in science and industry. Such charts have been found to be of value not only in portraying the present state of the art but also in planning the Bureau's programs for improving measurement capabilities to meet present and developing needs. As a summary collection, without description of the various devices, methods, and causes of uncertainty involved, the charts must be considered as provisional. Detailed discussions of some of them have already appeared in the literature and this may be expected for others.

Comments, suggestions, and additional information will be welcomed as aids both for improving the charts and for identifying important and urgent needs for measurements of greater accuracy or extended range.

R. D. HUNTOON, *Director*
Institute for Basic Standards
National Bureau of Standards

Contents

v

GENERALIZED CHART OF UNCERTAINTY IN MEASUREMENT

◇NBS◇

8/64

$\epsilon = k_3 Q^{1+n}$

$\epsilon = k_2 Q$

$\epsilon =$ ESTIMATED TOTAL UNCERTAINTY

$\epsilon = k_1$

ONE
PART
IN

10^8

5×10^6

10^6

10^4

10^2

1

UNCERTAINTY (ϵ/Q, log scale)

10^{-10}

1

10^{+10}

MAGNITUDE OF PHYSICAL QUANTITY (Q, log scale)

1. Introduction
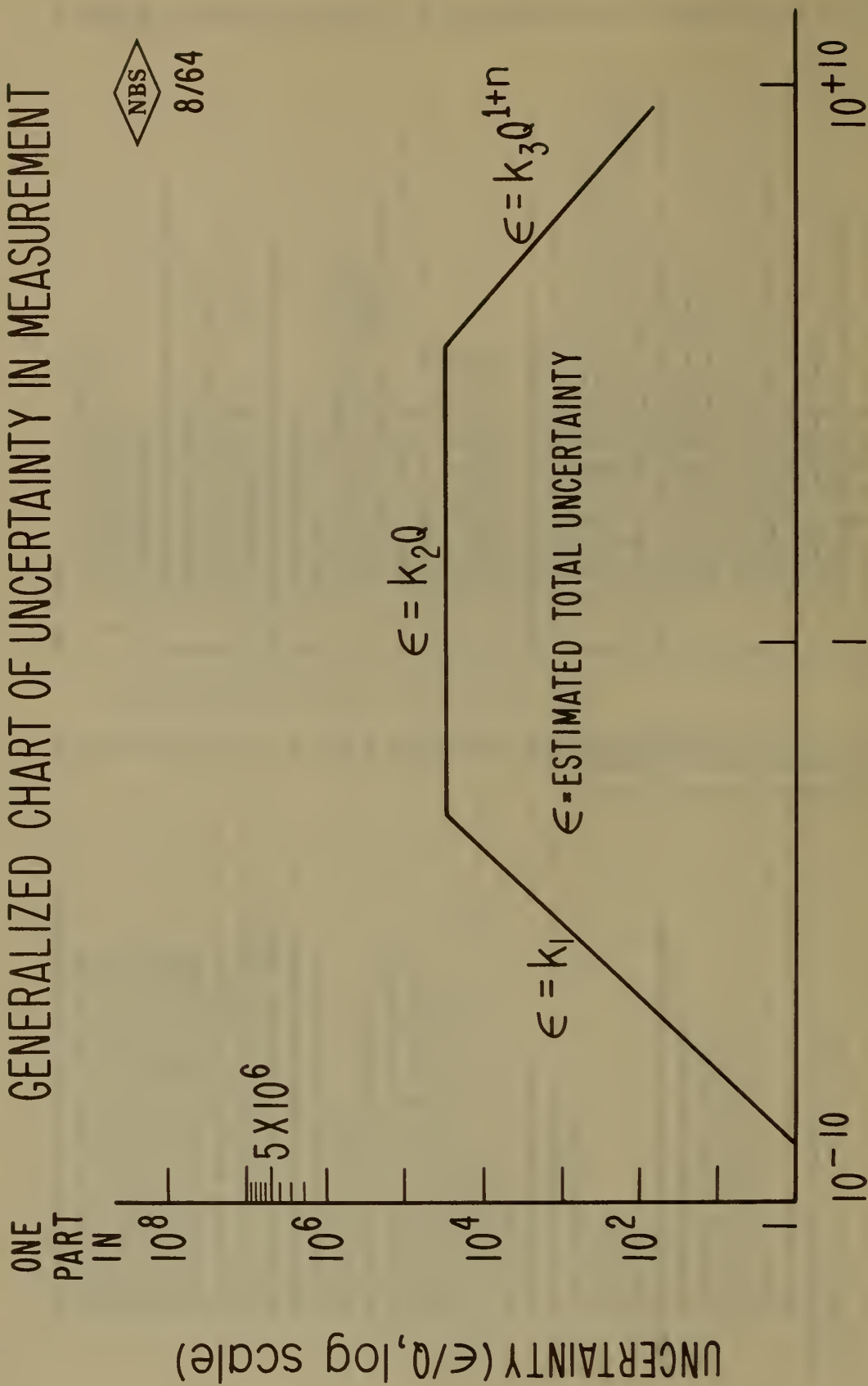
The "accuracy charts" shown herein are plots of the uncertainty associated with measurement of a physical quantity, or the calibration of physical standards or measuring instruments, over the range in which direct comparison with NBS standards is feasible. Some show present estimates of precisions or accuracies for NBS standards already available as calibration services to science and industry; others indicate values sought as near-term goals. The charts and their explanatory facing sheets have been prepared by many different project leaders at NBS, with coordination by H. W. Lance and R. C. Powell for radio-frequency standards.

Because of the extended ranges over which many physical quantities are required to be measured, the charts are plotted on logarithmic scales, to provide a better perspective of the enormous ranges involved. Increasing accuracy or precision (in more general terms, decreasing relative uncertainty) is shown as an increasing ordinate. We have chosen to express the left-hand scales in terms of one part in the indicated ordinate value, e.g., 1 in 5×10^4, which is equivalent to 2 parts in 10^5, 20 ppm, or 0.002 percent. The generalized form on page vi shows how the relative uncertainty is likely to vary with the magnitude of the physical quantity in typical cases. Such a chart provides a ready base on which one may indicate various techniques or instruments or plans, or plot the comparative accuracies associated with various echelons of calibration, from the international standards to the instruments on the factory bench.

A few charts similar to these were presented in several papers [1] at the 1962 National Conference of Standards Laboratories at the Boulder (Colo.) Laboratories of NBS. The present collection extends the number to 66. On the charts for some quantities, auxiliary parameters have been indicated, e.g., frequency for microwave power measurements. On others, e.g., neutron flux density, an auxiliary parameter considered to be of primary importance (here neutron energy) appears as the abscissa, but in such cases the accuracy stated refers to measurement of the subject quantity. However, the basis for estimating accuracy varies from chart to chart, as dictated by current practice in an individual laboratory to meet the demands of its field. For some quantities shown here, the values of absolute accuracy (uncertainty) include an estimate of the limits of systematic errors (both

constant and variable [2]) for calibration of typical high-quality inter-laboratory standards using the measurement process, equipment, and personnel of NBS. For others only the computed limits of precision are given, reflecting only repeatability under these conditions. In the latter case, the figure usually corresponds to three times the standard deviation of the observations from their average. The references below cover available statistical methods for evaluating and combining various estimates of uncertainty;[3,4] the various measurement techniques and their useful ranges,[5] and the many factors which must be considered in estimating overall uncertainties.[6] Some charts include shaded bands of uncertainty designated "Non-NBS State of the Art." These are estimates by various NBS staff members, gleaned from the technical literature, from manufacturers, or from the 1963 URSI survey;[7] any needed corrections will be welcomed. The reader interested in evaluating the accuracy of his own measurements is cautioned that allowance must be made for the inevitable deterioration of accuracy resulting from the sequence of events and environments between an NBS calibration and the point at which the calibrated instrument is used.

The qualitative or quantitative listing of needed improvements in accuracy or extension of range, as shown on charts or facing sheets, is the composite result of staff judgment and of statements made by industry and government agencies. Major contributions came from the Quality Control Project of the Aerospace Industries Association, the Measurement Research Conferences sponsored by AIA and NBS, contractors and laboratories of DoD, NASA, and AEC, and the various NBS Advisory Panels. "Objectives" shown as chart curves or mentioned in text must be regarded as subject to change because of shifting priorities and resources.

All the calibration services on physical quantities presently available from NBS are given in Miscellaneous Publication 250.[8] This also lists the services in precision measurement provided by the Bureau on such items as audiometric earphones, chromaticity of light sources, photographic objectives, gear tooth indexing, gamma-ray sources, magnetic permeability, dielectric constant, and fire endurance of structural columns. Miscellaneous Publication 260 [9] describes the specially prepared reference materials available from

1

stock—stainless steels and hydrocarbons for spectrometer calibration, viscometric oils, radioactive nuclides, alloys and ceramics of certified composition, and many others.

Comments are invited on any aspect of the charts: these may be directed to the editors. Inquiries or suggestions as to the extension of NBS services will be particularly welcome from persons concerned with high-precision measurements in research, development, or calibration, if they foresee difficulty in obtaining calibration accuracy adequate to their needs in the ranges of importance to them.

[1] Proceedings, National Conference of Standards Laboratories, 1962, NBS Misc. Publ. 248, available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, at $1.75. See papers by W. A. Wildhack, T. R. Young, E. C. Lloyd and B. L. Wilson, J. F. Swindells, F. L. Hermach, A. H. Morgan, R. C. Powell, R. E. Larson, John L. Dalke.

[2] Ibid., paper 2.1 by Churchill Eisenhart, paper 5.1 by W. J. Youden.

[3] A. G. McNish and J. M. Cameron, pp. 101–104; E. L. Crow, pp. 105–114, IRE Trans. Instr. **I–9.**

[4] *Chapter 23 of Experimental Statistics, NBS Handbook 91, available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402, at $4.25. A list of other NBS papers on the uncertainties associated with calibrations and measurements, either general or for specific variables, is available at no charge from the Office of Technical Information and publications, National Bureau of Standards, Washington, D.C., 20234.*

[5] Precision Measurement and Calibration, NBS Handbook 77 (Feb. 1961), available from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402: Vol. I, Electricity and Electronics, $6.00; Vol. II, Heat and Mechanics, $6.75; Vol. III, Optics, Metrology, and Radiation, $7.00.

[6] See, for example, R. C. Powell, R. M. Jickling, and A. E. Hess, IRE Trans. Instr. **I–7,** 270–274 (Dec. 1958).

[7] URSI National Committee Report, XIV General Assembly, Tokyo, Sept. 1963: Commission I, Radio Measurement Methods and Standards. In J. Res. NBS **68D** (Radio Science), No. 5 (May 1964).

[8] Calibration and Test Services of the National Bureau of Standards, NBS Misc. Publ. 250, available at 70 cents from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. For continuous updating, see the Federal Register.

[9] Standard Materials Issued by the National Bureau of Standards: A Descriptive List With Prices, NBS Misc. Publ. 260, available at 35 cents from the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 20402. Supplementary inserts are issued periodically.

II. Charts for Basic Physical Quantities*

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*For electric current (one of the six basic quantities of the Système Internationale), see page 26–27.

PRECISION OF WEIGHING

PEP 8/21/64

●-BALANCES & SCALES
△-ELASTIC DEVICES

STANDARD DEVIATION OF SINGLE WEIGHING

ONE PART IN

LOAD IN KILOGRAMS

4
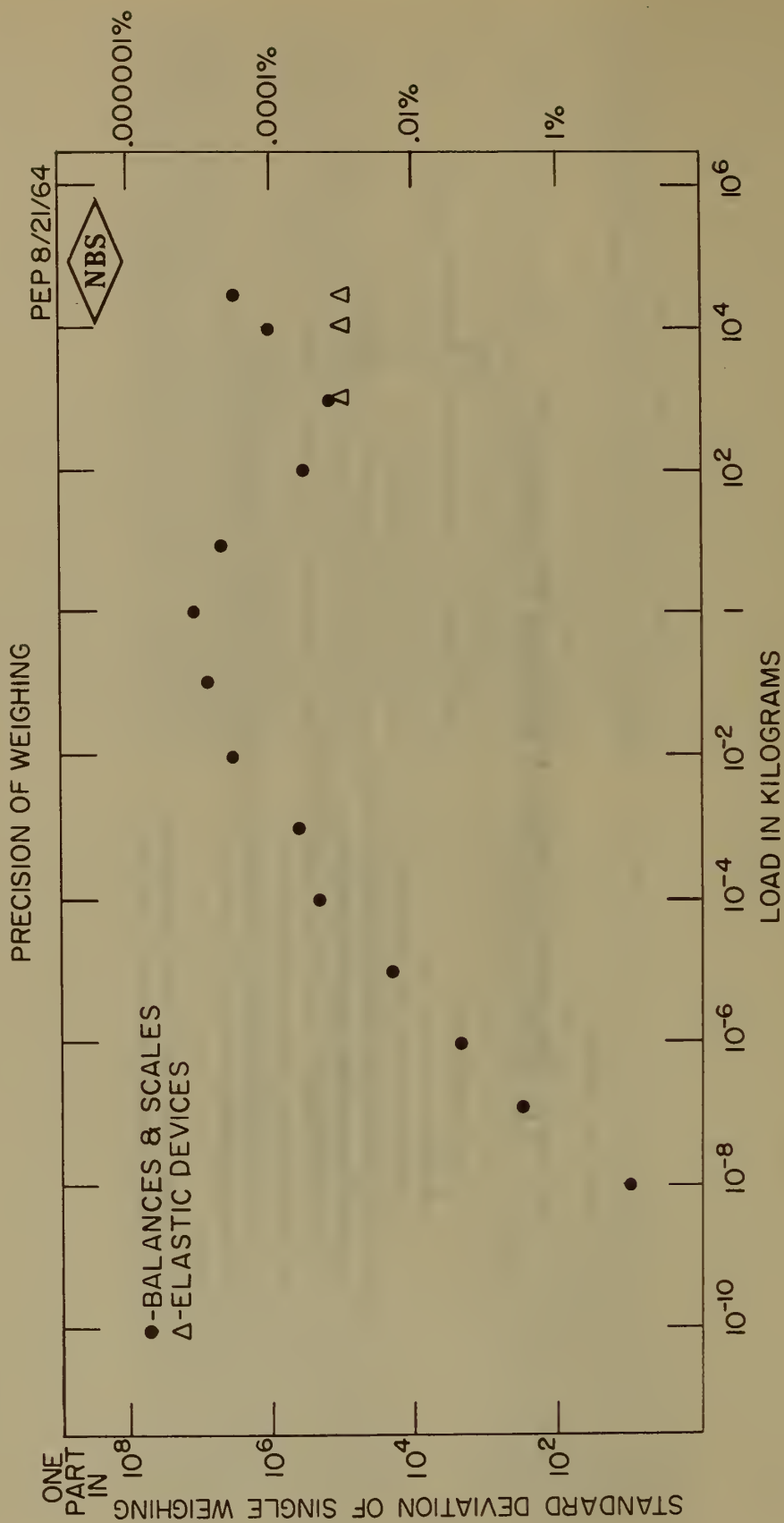
Mass Weighing

P. E. Pontius, *Section Chief*

State of the art: Black circles on the chart show estimates of the precision of a single weighing, expressed as one standard deviation, based on experience with selected equipment available at NBS, and with precautions against environmental disturbances. Overall uncertainty of the calibration process is dependent on the choice of redundancy in the design of the weighing procedure and the correction for systematic errors.

Triangles represent estimates of precision, expressed as one standard deviation, for values obtained by using a load cell of high sensitivity as a mass comparator in the calibration of large mass standards. Calibration at both higher and lower loads can also be made with this technique.

Observed readings on sets of mass standards sent in for calibration are now checked for consistency, analyzed statistically, and printed out by automatic data-processing equipment. The report provides corrections, referred to the national standard of mass, for apparent mass (used in conventional weighing procedures), true mass, and an expression for overall uncertainty of the calibration process (after correction for systematic errors from known sources).

Short-term objective: Multivariable application of statistical analysis and automatic data processing to identify systematic error from known sources.

ACCURACY OF LENGTH MEASUREMENTS AT NATIONAL BUREAU OF STANDARDS, 1964

—— EXISTING CAPABILITIES   ----- OBJECT OF EXISTING PROJECTS

INTERFEROMETRIC COMPARISON, KRYPTON 86 WAVELENGTH

LASER

NBS 5 METER BAR

GEODETIC TAPES

STEEL TAPES

GAGE BLOCK CALIBRATION

END STANDARDS

LINE STANDARDS

FRUSTRATED REFLECTION

JSB 9/1/64

NBS

ONE PART IN

10^8

10^7

10^6

10^5 UNCERTAINTY

10^4

10^3

10^2

10^1

10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4

LENGTH, INCH

10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2

LENGTH, METER

6

Length

J. S. BEERS, *Project Leader*

State of the art: The uncertainty plotted is based on three-sigma limits for random errors plus an allowance for systematic error. Uncertainty in refractive index for krypton 86 light in ambient atmosphere fixes existing capability for interferometric comparison of wavelength as shown at 1 part in 4×10^7 in visible range.

Industry needs: Calibration of gage blocks to a few tenths microinch is asked by a number of significant industries such as manufacturers of bearings, diesel engines, and machine tools. Gear calibration for space, aeronautics, defense. Automated reading of many-intervalled scales by light wavelengths. For satellite-tracking baselines, atomic accelerators, 1 part in 10^6 for 100 meters.

Short-term objectives: Wringing film determination by frustrated reflection to be applied to 0.1 microinch gage block calibration. Line standard interferometer to be used in calibration. Calibrate Mössbauer line for iron, seek stronger source, build into geodometer. Investigate stabilized frequency laser source usable for indefinitely long distances. Improve facilities for thread gages, optical flats, etc. Study wave front shape by interferometry.

7

FREQUENCY

FREQUENCY IN HERTZ

REFERENCE STANDARDS
EXISTING CAPABILITY
5 YEAR OBJECTIVE
CALIBRATION SERVICE
EXISTING CAPABILITY
5 YEAR OBJECTIVE
NON-NBS STATE OF THE ART

SIGNAL SOURCES

NBS

RESONANCE FREQUENCY
(CAVITY WAVEMETERS)

UNCERTAINTY (ONE PART IN)

8
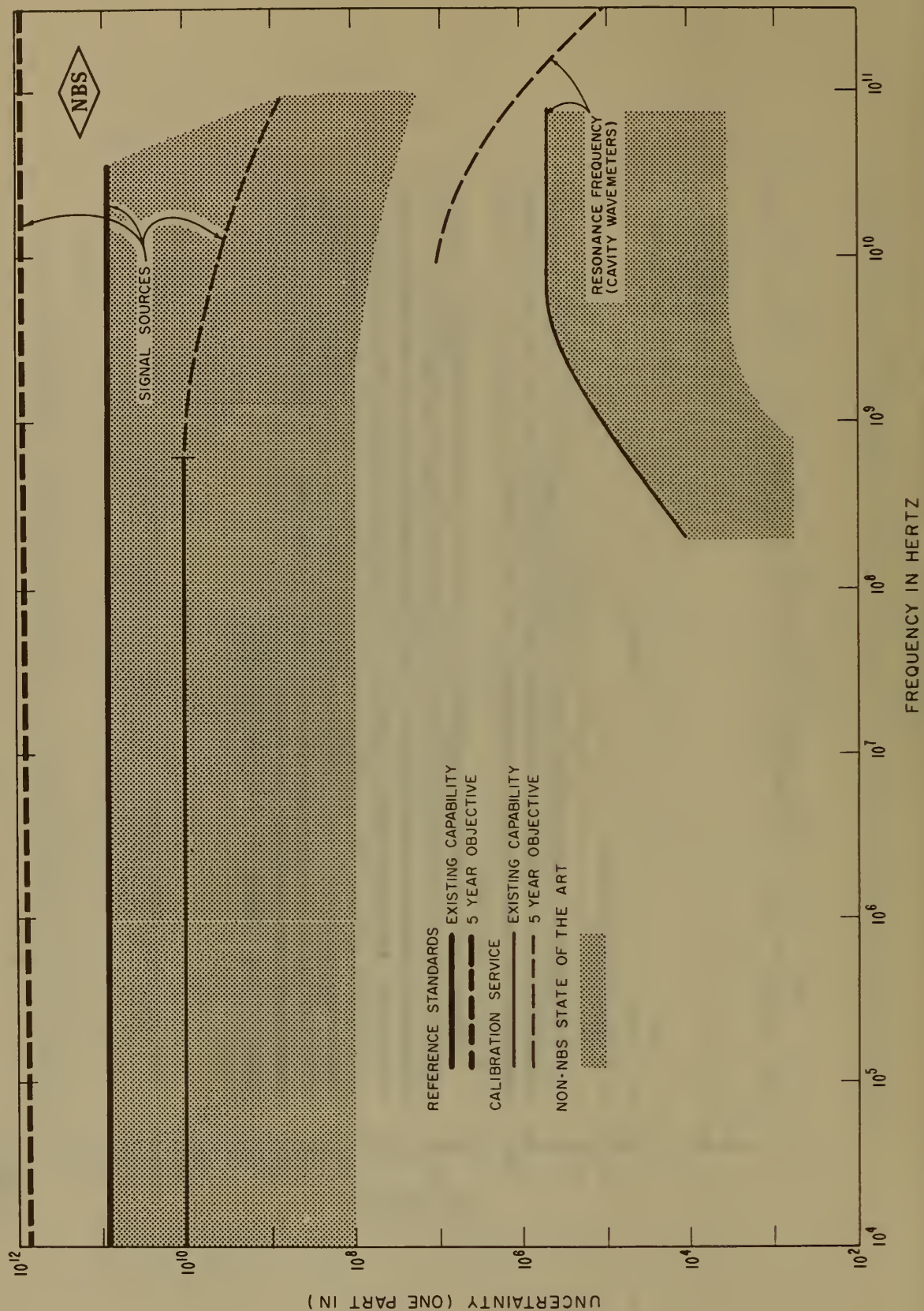
Frequency and Time Interval

R. C. Mockler, *Section Chief, Standards*
A. H. Morgan, *Section Chief, Dissemination Research*

D. H. Andrews, *Section Chief, Broadcast Services*
J. H. Shoaf, *Project Leader, Dissemination*

General: The term "precision," when used in connection with the NBS frequency standards, refers to the extent to which a measurement of frequency is reproducible. Used in this sense the measure of precision would include contributions from both the standard itself and whatever source of frequency is being measured. The most commonly used measure of precision for NBS measurements of frequency is the standard deviation of the mean associated with the comparison data.

The term "uncertainty" refers to the degree to which the atomic frequency standard approaches the value of the idealized resonance frequency for the cesium atom in its unperturbed state. This uncertainty figure is consistent with the values obtained by other reliable standards laboratories in foreign countries (i.e., England, Switzerland, etc.).

The lower limit for short time intervals (reciprocal frequency) is of course limited by equipment and techniques for determining the end points of a time interval. Time interval measurements are based upon the atomic definition of the second as adopted by the Twelfth General Conference of Weights and Measures in October 1964.

Existing capability: The curve for existing capability of signal sources is based primarily on cesium beam standards (i.e., 6 parts in 10^{12} accuracy).

The curves for existing capabilities for calibration services represent, in general, the announced services available. Calibration service for special requests, where extended frequency ranges or slightly lower uncertainties are necessary, may be made contingent upon demands.

The lower limit on the range for calibration of cavity resonators is, of course, based on the nature of resonant devices (i.e., limited in general to the microwave region). The limitation on accuracy for resonance frequency is the uncertainty of resettability of cavity wavemeters, etc. (dial graduations, coarse verniers, etc.).

Five-year objectives: The curve for future objectives is based on improved techniques and better cesium standards as well as other atomic standards such as the thallium beam or hydrogen maser. Approximately one order of magnitude less uncertainty may be achieved.

It is planned to eliminate the cavity resonator calibration service below X-band in the near future.

State of the art: The existing capabilities also represent the upper limit of the non-NBS state of the art. The width of the band is determined by the uncertainty range of high-quality standards.

IMPROVEMENTS IN THE ACCURACY
OF THE U.S. FREQUENCY STANDARD
(USFS)

NBS

H MASER, Cs BEAM, T ℓ BEAM. (FUTURE)

NBS – II (Cs BEAM)

A106 Cs BEAM

EPHEMERIS TIME (ET)

QUARTZ CLOCK (UT 2)

SHORT T CLOCK (UT 0)

UNCERTAINTY (ONE PART IN)

10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4}

1920 1930 1940 1950 1960 1970

YEARS

TIME INTERVAL

REFERENCE STANDARDS

——— EXISTING CAPABILITY

– – – 5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

TRANSMITTED - WWV

UNCERTAINTY (ONE PART IN)

TIME INTERVAL IN SECONDS

ACCURACY OF REALIZATION OF THE
THERMODYNAMIC TEMPERATURE SCALE

12

Accuracy of Realization of the Thermodynamic Temperature Scale

J. P. Evans, L. A. Guildner, H. J. Kostkowski, H. H. Plumb, J. L. Riddle, *Project Leaders*

State of the art: While the Thermodynamic Kelvin Scale (TKS) is completely defined by assigning a value to the triple-point of water, this does not by itself enable one to realize the Scale at any other temperature. Using thermodynamic relations, however, the Scale is realized in different temperature ranges using the best available technique in each range. The Scale is put to practical use by determining the Kelvin temperatures of appropriate fixed points (freezing points, boiling points, etc.). Determinations are also made, between the fixed points, of the deviations from the TKS resulting from the properties of the practical instruments used for interpolation between fixed points. The temperature scale covered by the chart is divided into six ranges according to the techniques used for determining thermodynamic temperatures. It is a continuing NBS responsibility to develop techniques for more accurate realization of the Scale and for the utilization of the results of similar work in other scientific institutions. Work directed toward the improvement of the Scale in range III on the chart is in progress at the NPL in England and the NRC in Canada. Consequently, no similar work is planned at NBS.

Industry needs: Since nearly every physical property of matter has some degree of dependence on temperature, the need for temperature measurements which can be expressed on the TKS exists to a greater or lesser extent in every technological process and scientific activity. For example, thermodynamic temperatures are required in scientific laboratories studying and measuring the ther-

modynamic properties of matter, and in industries concerned with methods of power generation such as steam turbines, jet and rocket engines, and atomic plants. The aerospace industries and chemical and refrigeration industries are only examples of the industry-wide need for thermodynamic temperatures. In addition, the International Conference on Weights and Measures is expected, in 1968, to make significant changes in the International Practical Temperature Scale which will be based upon the best available knowledge of the TKS at that time. It is therefore important that NBS be in a position to contribute as much as possible to the data upon which such changes will be based.

Short-term objectives: Continued effort on temperature range I, studies of the production of temperature below 1 °K, and the improvement of thermometric methods. Range II, development and utilization of ultrasonic thermometry to realize the TKS between 1 and 20 °K to within ±0.1 percent or better. Range IV, development of a gas thermometer for the realization of the TKS between 273 and 1336 °K to within ±0.01 °K at 1336 °K. Range V, development and utilization of photoelectric pyrometry for the realization of the TKS to within ±0.1 °K at 1336 °K and to within ±5 °K at 4300 °K. Range VI, continued studies of spectroscopic techniques of measuring temperatures in arc plasmas to improve significantly the present capability of about 5 percent.
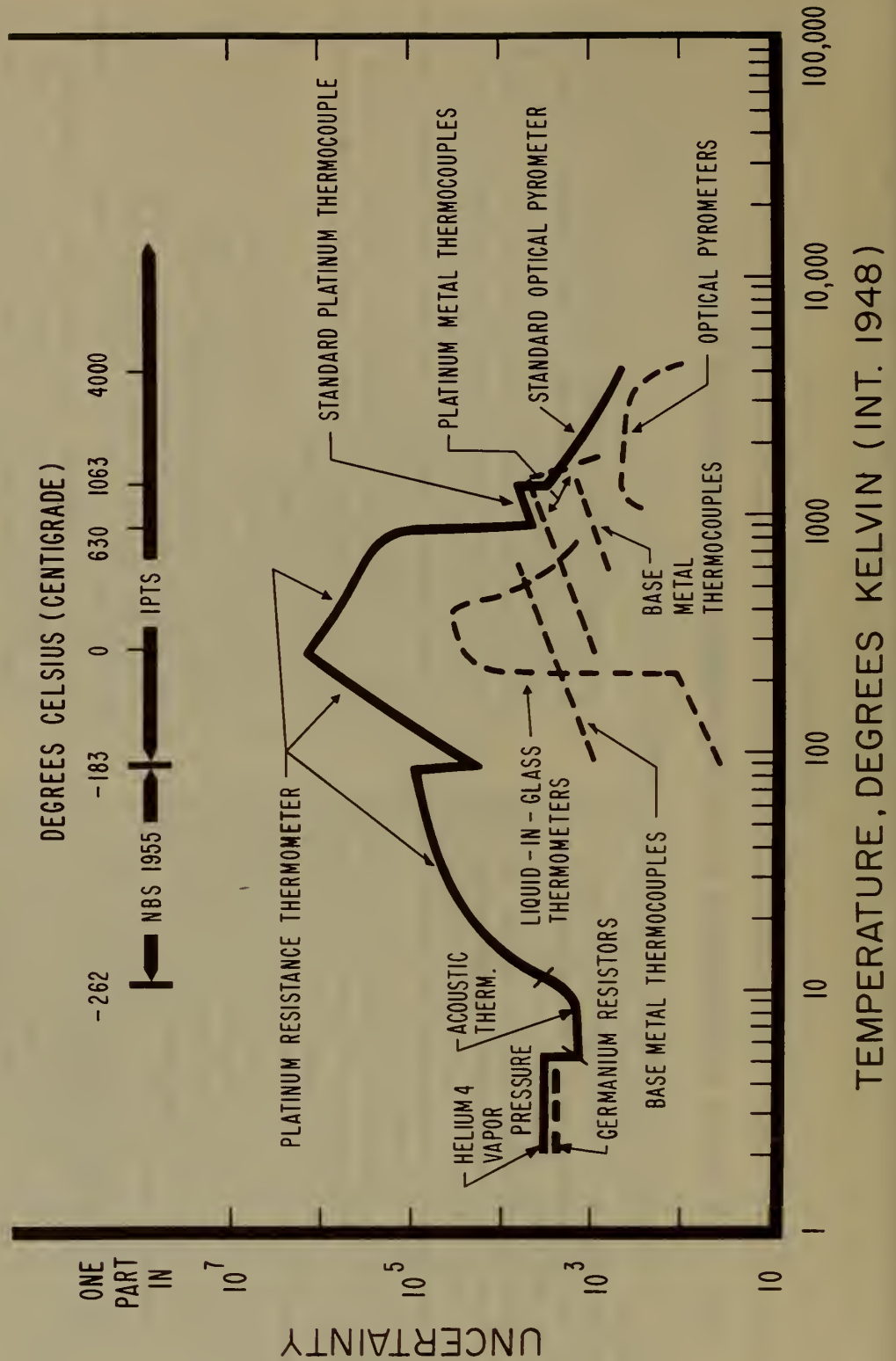
CALIBRATION OF TEMPERATURE-MEASURING INSTRUMENTS
JFS 8/6/64

Practical Temperature Scales: Calibration of Temperature-Measuring Instruments

H. H. Plumb, W. R. Bigge, G. W. Burns, E. Lewis, Jr., G. F. Williams, *Project Directors*

At NBS the International Practical Temperature Scale (IPTS) is realized to serve as a common basis for defining temperatures in the United States. Below the lower limit of temperatures defined by the IPTS at 90 °K (−183 °C), a second scale, known as the NBS Provisional Scale of 1955 (NBS 1955 Scale), has been devised for use down to about 12 °K. In the range 2.0 to 5.22 °K a third scale, known as the T_{58} Scale (helium 4 vapor pressure), is also maintained. Recently the gap between 5 and 12 °K has been bridged by a scale based upon work with the newly developed NBS acoustic thermometer. Calibration services, provided for government agencies and private organizations and individuals, are based upon these scales.

The solid curves in the chart represent the accuracy with which the three scales are realized, using the specified instruments of interpolation between the defining temperatures of the scales. The dashed lines show assigned limits of error for widely used calibration services. These limits of error are largely judgment-type limits

based upon estimated magnitudes of the known sources of error. In nearly all cases there are insufficient data of a kind which will permit statistical analysis of the contribution of a particular potential source of error.

In several temperature ranges, work is currently in progress whose purpose is the improvement and extension of calibration services for temperature-measuring instruments. At −183 °C (90 °K), the temperature of the oxygen point, apparatus is being developed which will materially improve the accuracy with which this point on the IPTS is realized. For use at high temperatures, a photoelectric pyrometer has been developed which will improve the NBS realization of the IPTS above 1063 °C (gold point). This instrument permits the more accurate calibration of commercial photoelectric pyrometers which are now becoming available. In addition, the development of standards and facilities for the calibration of high-temperature thermocouples is at an advanced stage.

PRECISION AND ACCURACY OF NBS PHOTOMETRIC STANDARDS
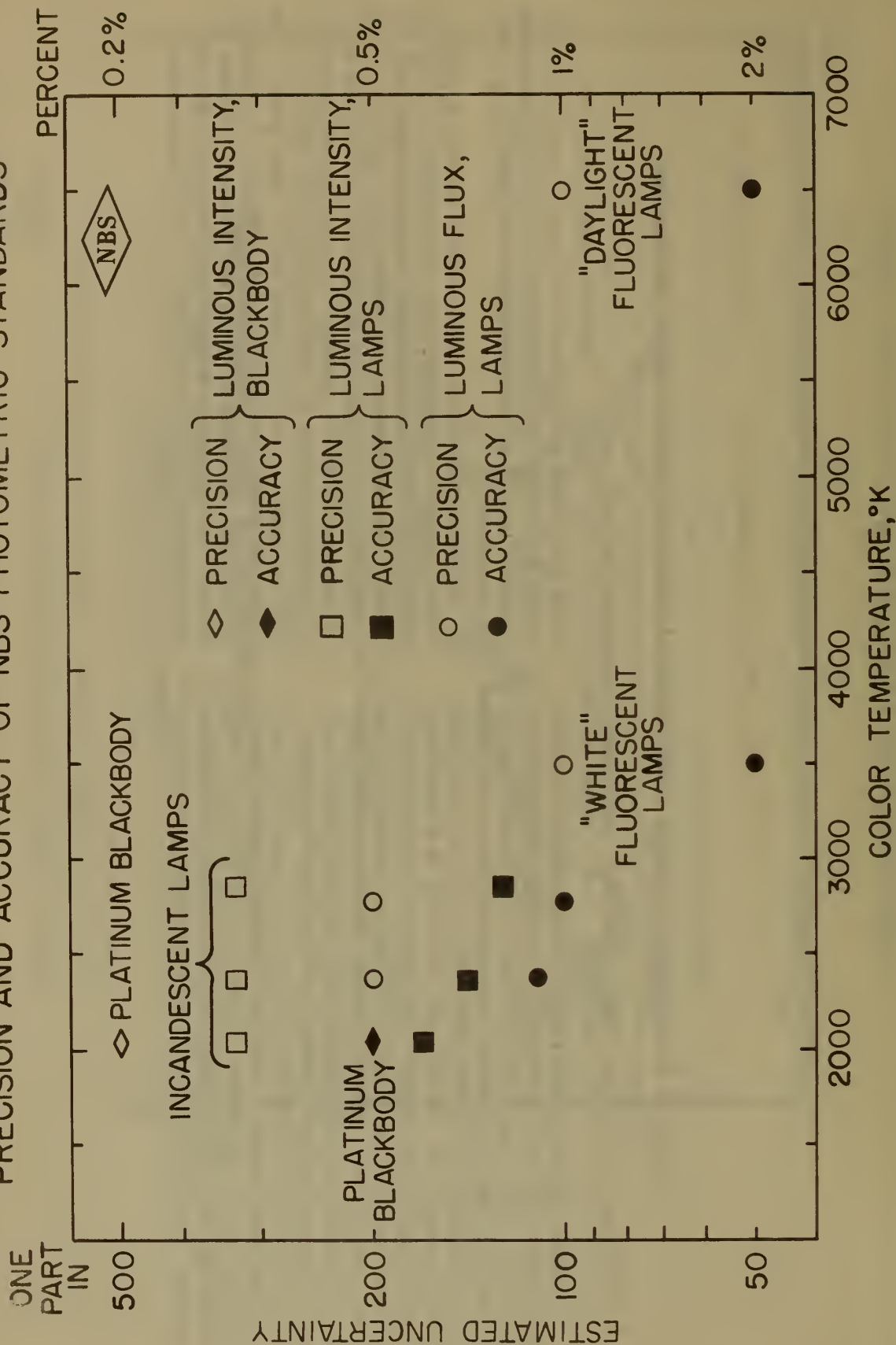
NBS Photometric Standards

R. P. TEELE, *Project Leader*

State of the art: The current system of photometric units and standards is based on the luminance (candela/cm²) of a blackbody at the temperature of freezing platinum (2042 °K), which is reproducible to within about 0.5 percent. The candela is defined as the luminous intensity of 1/60 of one square centimeter of projected area of such a radiator. The luminous flux of other standard sources (rate of energy radiation in lumens) is the integral of the product of monochromatic luminance times its relative luminous efficiency, taken over all wavelengths of visible spectrum, and conventionally referred to the equivalent color temperature of a fictitious blackbody. The uncertainty of luminous intensity of a standard source (flux reaching unit area of a unit sphere) is also plotted against color temperature, since that is a more important influence than the variation of intensity with the inverse square of distance. Fluorescent lamp standards, which have mercury lines superimposed on a continuum, are so different in spectral distribution from thermal radiators relative to which they are calibrated that their photometric assignments are uncertain by about 2 percent, with the uncertainty in the photometric assignments of incandescent lamp standards between these two values of uncertainty.

Industry needs: While increased accuracy of all these standards would be desirable, it is not urgent.

Short-term objectives: Together with other national standardizing laboratories, NBS is investigating the feasibility of placing the system of photometric units and standards on a radiometric base in which radiant flux of a given wavelength in the visible region of the spectrum would be assigned a value of luminous efficacy (for example, 680 lumens per watt at 555 nanometers). The goal is to attain a reproducibility better than about 0.25. In addition, NBS is investigating a radiometric procedure for assigning photometric values to fluorescent lamps which, it is hoped, will reduce the uncertainty of these values to less than 1 percent.

III. Charts for Electrical Quantities, d-c to 30 kHz

CALIBRATION OF STANDARD RESISTORS

20
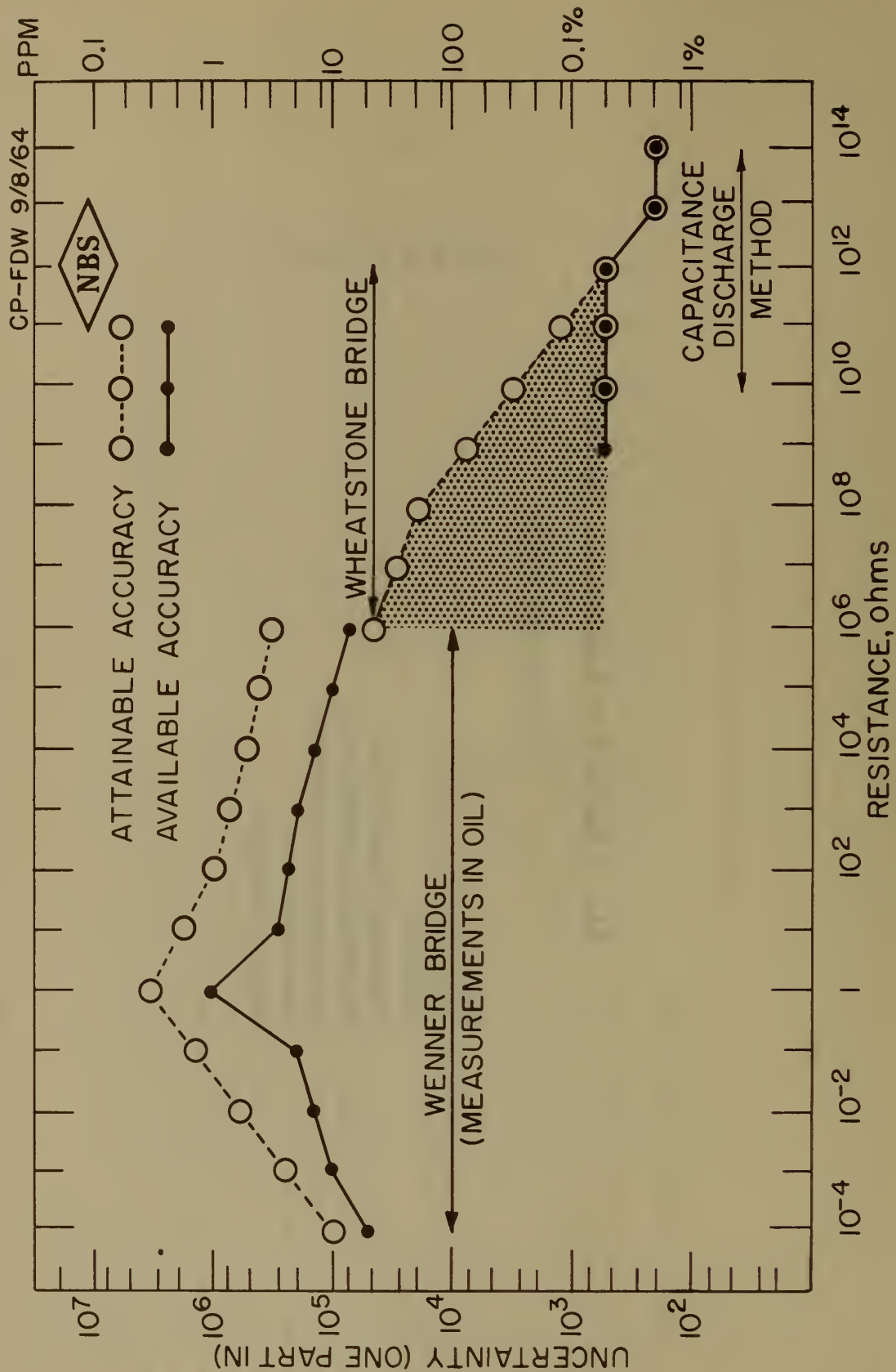
Calibration of Standard Resistors

H. KRIDER, D. RAMALEY, *Project Leaders*

All resistors having nominal values up to 10^{12} ohms are calibrated by comparison with NBS working standards. By means of accurately established ratios, these working standards are evaluated periodically in terms of the legal unit of resistance maintained with a highly stable group of Thomas-type 1-ohm resistors. The legal unit approximates very closely the defined unit, the absolute ohm. Resistors having values of 10^{10} ohms and above may be calibrated in terms of the units of capacitance and time using the capacitor discharge method.

Precision resistors in oil, at 25.0 °C, Wenner Bridge: In the range 10^{-4} to 10^{3} ohms, the solid points on the accompanying chart indicate currently *available* accuracies (uncertainties) listed in the fee schedule for measurements in terms of the legal unit. The total uncertainties are based on estimated limits of systematic error, plus three times the standard deviation for random errors. These total uncertainties pertain to calibration measurements made for the public by established methods on commercially made, high-quality standard resistors, and at an established fee. The open circles indicate the maximum attainable accuracy (minimum uncertainty of

state-of-the-art measurements) which can be made by painstaking procedures with great effort on "ideal" resistors.

Two-terminal resistors, 10^{3} to 10^{12} ohms, in air, Wheatstone Bridge: Open circles connected by dotted line show accuracy attainable under ideal conditions. In range 10^{1} to 10^{12} ohms, available accuracy depends largely on the characteristics of the resistor being calibrated and will be in the shaded area. High-quality wire-wound resistors up to 10^{8} ohms having reasonably low temperature coefficients may be calibrated regularly with an uncertainty not exceeding a few hundredths of one percent. Acceptable metal film or deposited carbon "standards" 10^{8} to 10^{12} ohms are calibrated with a stated uncertainty of 0.2 percent.

Resistors 10^{10} ohms and above, capacitance discharge method: In this area the attainable and the available accuracies coincide; "ideal" resistors do not exist.

Short-term objectives:

1. To increase the available accuracy in the calibration of 10^{4} ohm standards approaching the characteristics of "ideal" resistors.

2. To increase the attainable accuracy in high resistance measurements.

21

CALIBRATION OF STANDARD CAPACITORS

ATTAINABLE ACCURACY RELATIVE TO THE NBS UNIT OF CAPACITANCE
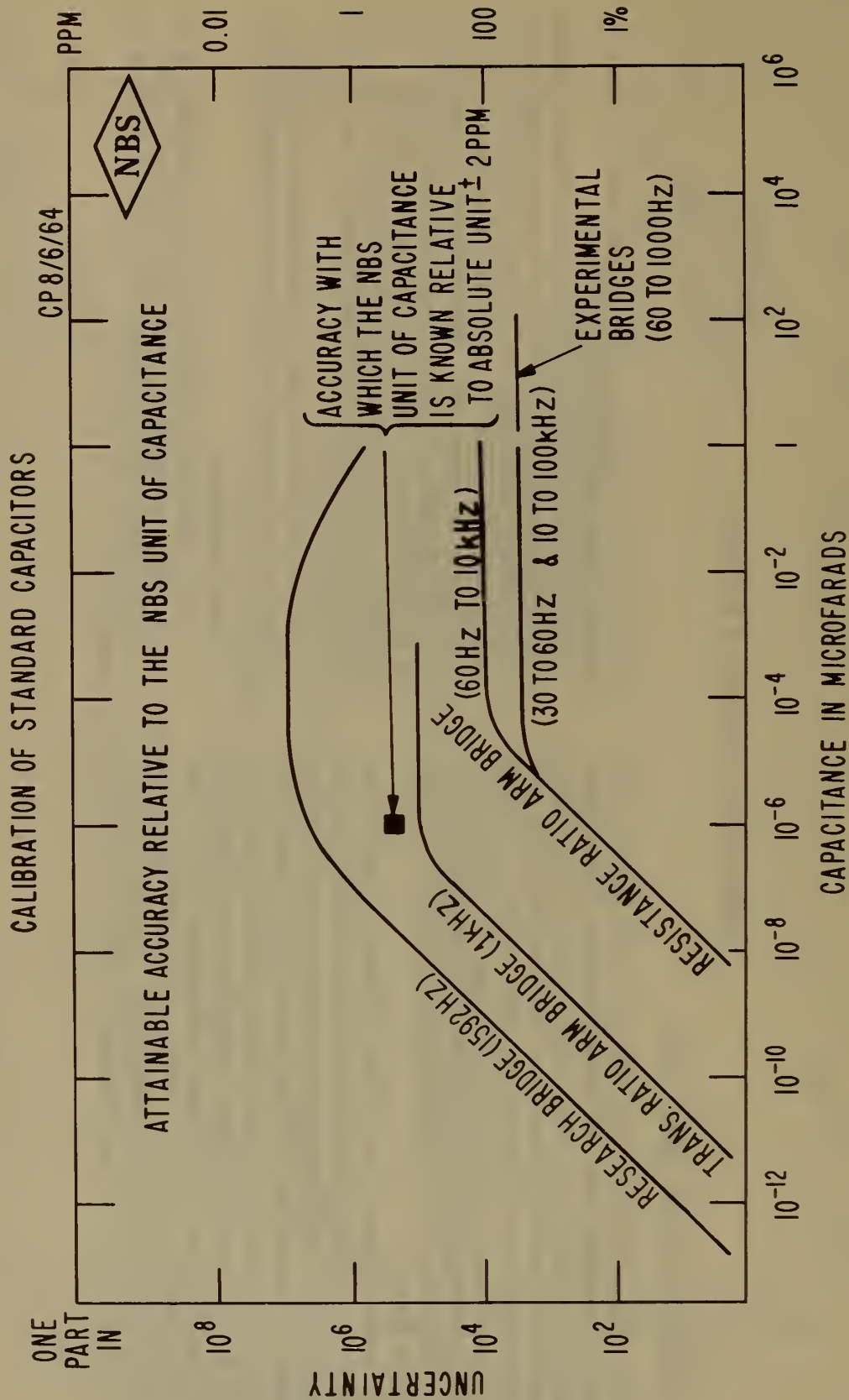
Calibration of Standard Capacitors

J. J. MORROW, T. L. ZAPF, *Project Leaders*

Standard capacitors are calibrated by comparison with NBS working standards of capacitance. These working standards generally are components incorporated into various a–c bridge structures. Other individual portable standards having nominal values on the decimal scale are used as reference standards for calibrating the bridges used in everyday calibration work. These reference standards have values ranging from 1 picofarad (pF) to 10 micofarads (μF). At the low end of this scale the 1–pF and 10–pF standards are hermetically sealed capacitors of NBS design and construction. The 1–pF standard is evaluated by comparison with the NBS computable capacitor; its value is projected upwards by means of accurate 1:10 ratios established with close-coupled transformer-type ratio arms.

The accompanying chart indicates the accuracies which have been attained at NBS in measurements employing various types of a–c bridges. It is not feasible to show on this chart the widely varying accuracies available in the fee schedule calibration of many different types of commercial standard capacitors covering 12 orders of magnitude. As an indication of what may be expected, it can be stated that the lowest value standard currently accepted for calibration is a three-terminal air capacitor having a nominal value of direct capacitance 0.001 pF; this is calibrated with a total uncertainty of 0.3 percent, the total consisting of the estimated limits of systematic error plus three times the standard deviation caused by random variations. The least uncertainty (0.002 percent at a frequency of 1000 Hz) pertains to the calibration of modern, hermetically sealed, three-terminal standards having low temperature coefficients of capacitance. At intermediate values of capacitance, the uncertainty of measurement at 1000 Hz is 0.02 percent. Polystyrene capacitors of good quality, 10 to 100 μF, can be calibrated with an uncertainty of 0.5 percent at frequencies in the range 100 to 1000 Hz. No capacitors are accepted for calibration at test frequencies less than 65 Hz, although some experimental work has been done at low frequencies.

Short-term objectives:

1. To improve capabilities for measurement of large values of capacitance.
2. To decrease the uncertainty in knowledge of loss factor.

23

CALIBRATION OF STANDARD INDUCTORS

CP 8/13/64

NBS

ATTAINABLE ACCURACY O--O--O
AVAILABLE ACCURACY ●——●——●

100HZ

400HZ

1000HZ

10kHZ

0.1 TO 10kHZ

UNCERTAINTY (ONE PART IN)

INDUCTANCE, HENRIES

24
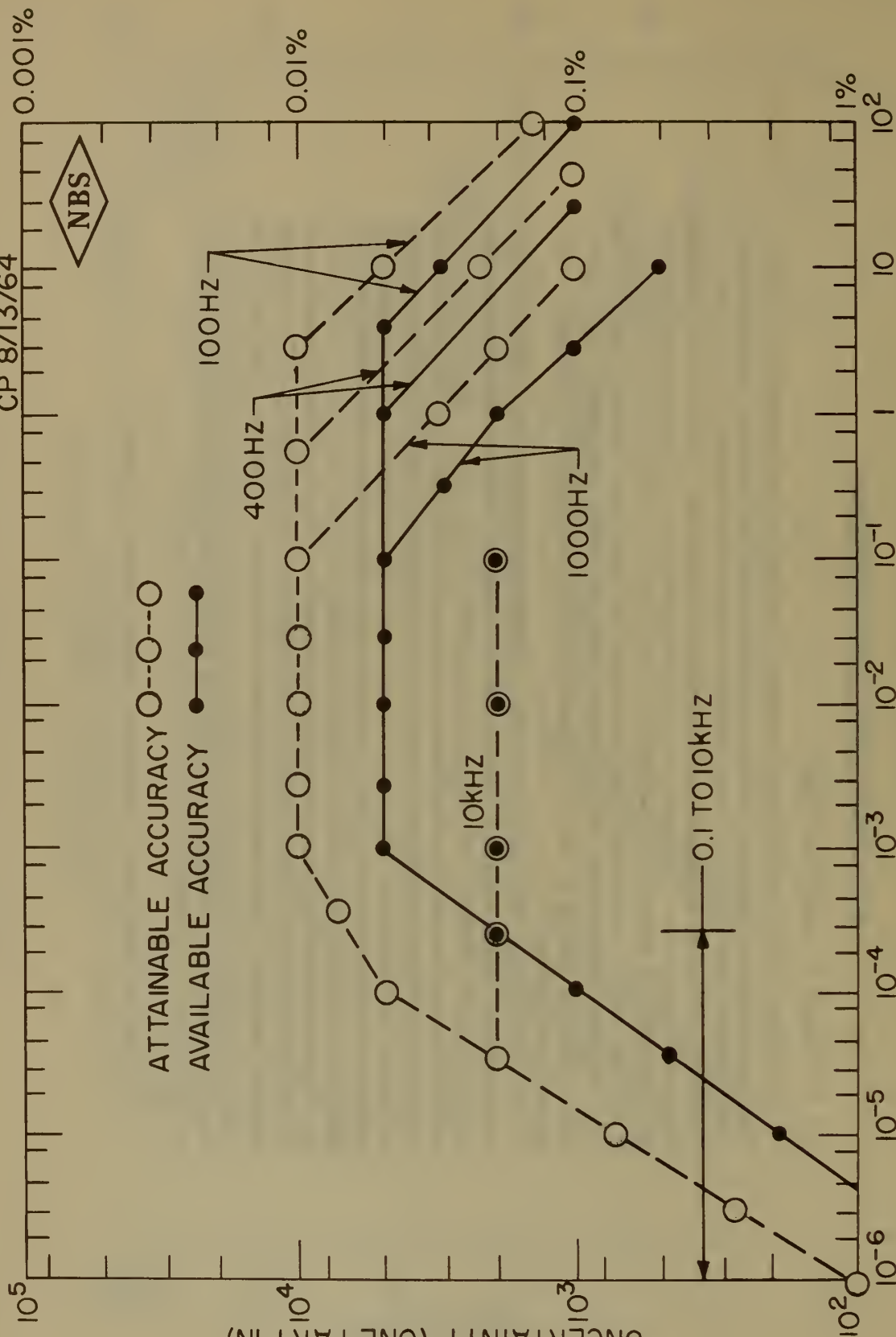
Calibration of Standard Inductors

J. J. Morrow, T. L. Zapf, *Project Leaders*

Standard inductors having nominal values of 50 microhenries or more are calibrated by comparison with NBS working standards. These working standards are calibrated periodically using a Maxwell-Wien bridge. Standards of lower nominal value, inductors of odd value, and mutual inductors intended for use in a-c bridge measurements are calibrated directly with the Maxwell-Wien bridge. (Mutual inductors used in magnetic measurements are calibrated by comparison with working standards of mutual inductance using direct current.)

On the accompanying chart the solid points indicate currently available accuracies (uncertainties) in the calibration of commercially available standard inductors, by established calibration procedures, at established fees. Under more closely controlled environmental conditions, and with greater effort, measurements on "ideal" inductors can be made with attainable accuracies (uncertainties) approaching those indicated by the open circles.

NBS is not aware of any urgent requirement for increased accuracy in inductance measurements. Some interest in enhanced accuracies at low values of inductance has been indicated. Investigations presently under way will eventually increase capabilities in this area.

CURRENT AND CURRENT RATIO
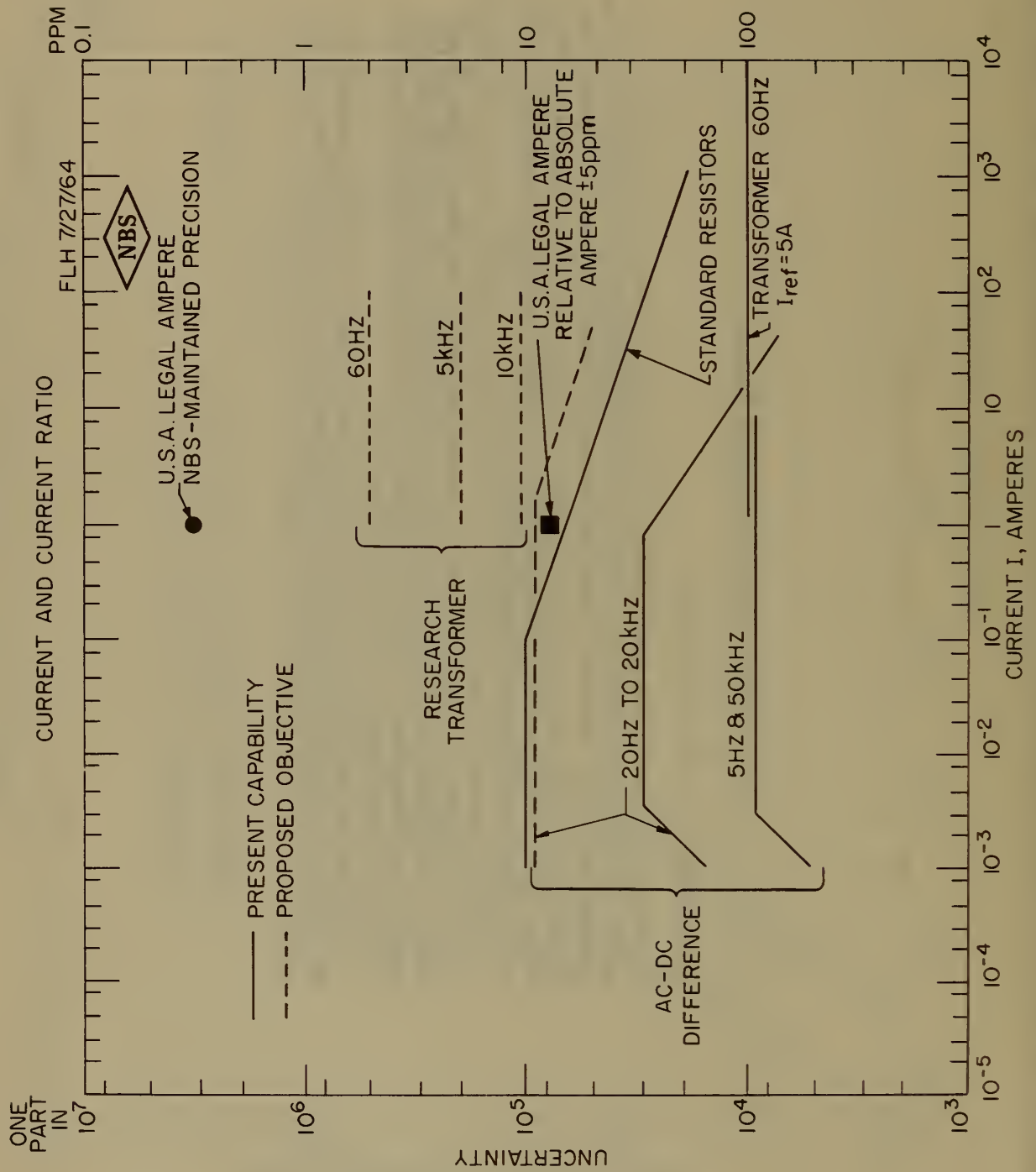
Current and Current Ratio

F. K. HARRIS, F. L. HERMACH, *Section Chiefs*

State of the art: The absolute ampere is realized by a current balance "weighing" to a few parts per million. The NBS (legal) ampere is estimated to be 12 ± 5 ppm above the absolute ampere, and is monitored to within ±0.3 ppm by use of proton gyromagnetic ratio and calibrated coil; d–c values above and below 1 ampere are realized by standard resistors and d–c potentiometer; a–c values are realized with ac–dc transfer standards and the same d–c standards. Estimated accuracies shown are for calibration of ideal reference standards (perfectly stable and unaffected by environment) and include 3 standard deviations plus estimated systematic errors; accuracy of ratio I/I_{ref} is shown for ideal transformers.

Industry needs: Nonmagnetic facility at Gaithersburg to expedite work on absolute ampere, gyromagnetic ratio, and speed of light; accurate measurements are presently possible only 1 to 5 in early morning. More accurate standards for steady-state d–c and a–c measurements.

Short-term objectives: Detailed plans for nonmagnetic facility. Improvements in Pellat-type balance for absolute ampere. Improvement of ac–dc transfer standards. Improvement of a–c ratio and extension to higher currents with transformers and a–c current comparators. D–c current comparator.

d–c VOLTAGE AND VOLTAGE RATIO

FLH 9/14/64

NBS

COMPARISON OF STANDARD CELLS

POTENTIOMETER AND VOLTAGE DIVIDER
V_{ref}=1 VOLT

U.S.A. LEGAL VOLT(NBS)
RELATION TO ABSOLUTE VOLT: 12±5 ppm

HIGH-VOLTAGE DIVIDER
V_{ref}=1 VOLT

PRESENT CAPABILITIES
PROPOSED OBJECTIVES

VOLTS, V

UNCERTAINTY

ONE PART IN
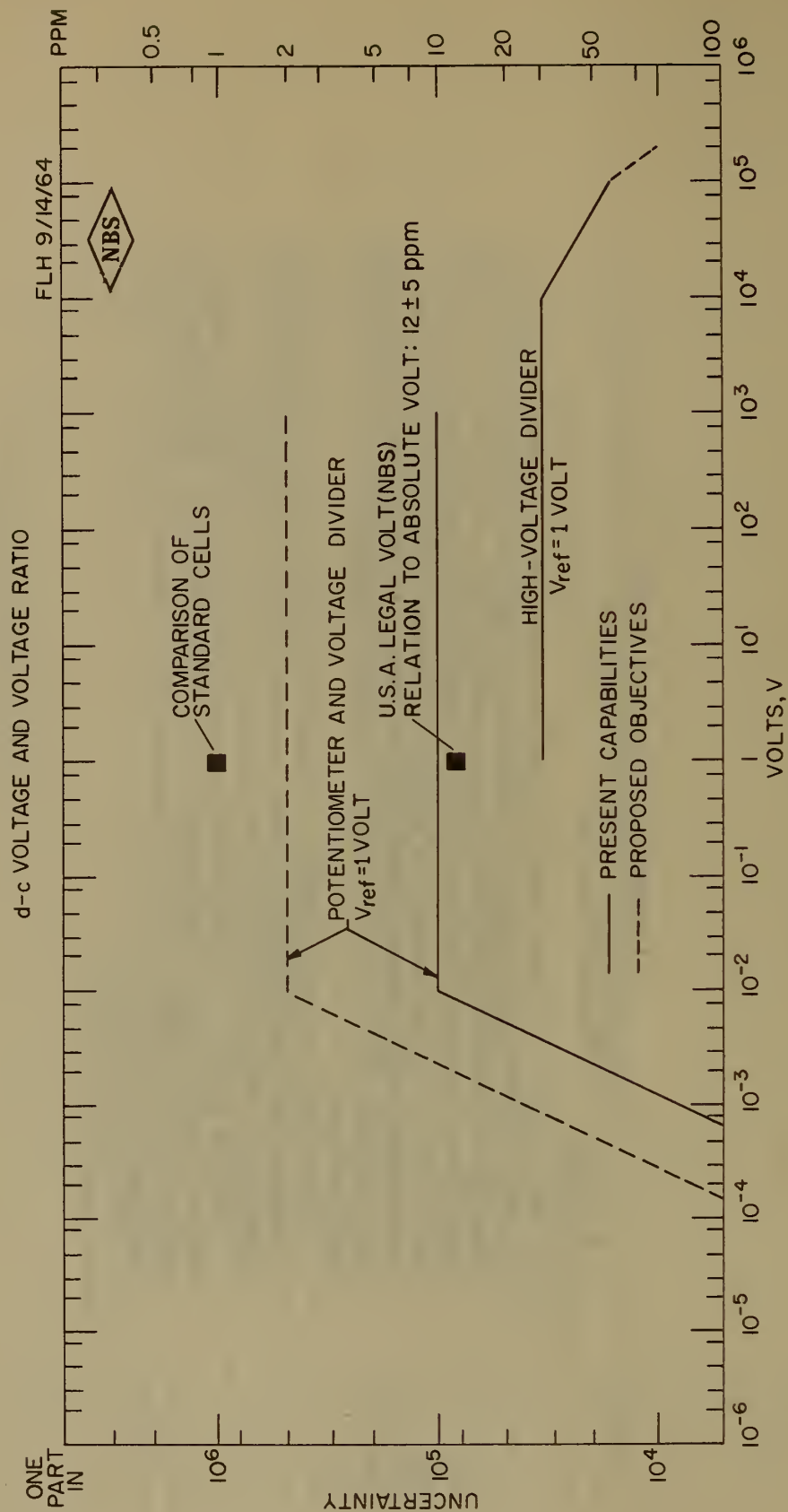
D-C Voltage and Voltage Ratio

W. Hamer, F. K. Harris, F. L. Hermach, F. R. Kotter, C. Peterson, *Section Chiefs*

Mrs. B. A. Wickoff, *Project Leader*

State of the art: The absolute volt is realized by passing a "weighed" ampere through a Thomas-type 1-ohm resistor to measure emf of standard cells. The USA legal volt is estimated to be 12±5 ppm above the absolute volt; it is monitored in terms of the USA legal ohm and ampere to within ±1 ppm. Standard cells are calibrated to within ±1 ppm,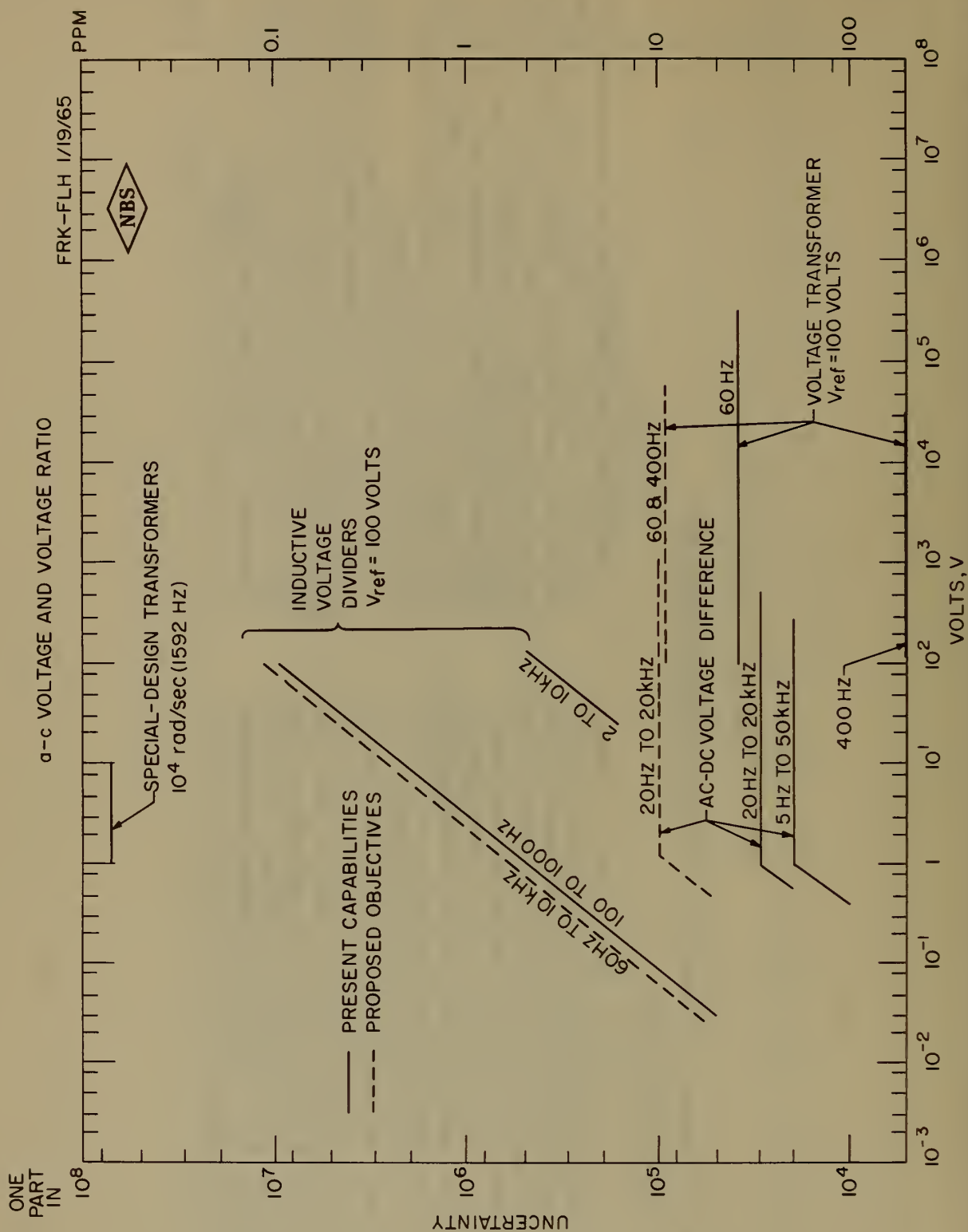 relative to legal volt. Measurements above and below 1 volt are made with ratio standards (potentiometers and voltage dividers); estimated accuracies shown are of ratios V/V_{ref}, and include 3 standard deviations plus estimated systematic error, for calibration of ratio standards assumed to be ideal (perfectly stable and unaffected by environment). A calibration service is available for determination of the ratio factor of pulse voltage dividers under single-pulse conditions. The calibrating pulse has a rise time of about 1 μsec, a length of about 12.5 μsec, and an amplitude of from 20 to 100 kV. The accuracy depends on the performance of the divider being calibrated and is in the range of 1 to 3 percent.

Industry needs: More accurate legal volt, closer to absolute volt. Voltage balance analogous to Rayleigh current balance. Improved standard cells, lower temperature coefficient, not requiring hand carrying. Stable reference at 1000 V. Precision d-c dividers accurate to within ±2 ppm of ratio under full voltage (to 1 kV). Measurement of pulse voltages in microsecond range up to 200 kV. Measurement of 100 kV to within ±10 ppm or better for atomic energy-level scale. USA embarking on high-voltage d-c transmission; needs improved techniques of measurement.

Short-term objectives: Techniques and equipment for measuring Zener diode voltages. Study of voltage balance for absolute measurement. Study pressure and temperature coefficients, effect of D_2O, in standard cells. Attain accuracy to within ±2 ppm for potentiometers and for voltage dividers under full voltage (to 1 kV). Improvement of the accuracy of high-voltage pulse-amplitude measurement to 0.5 percent and extension of the range to 300 kV.

a-c VOLTAGE AND VOLTAGE RATIO

FRK–FLH 1/19/65

NBS

PPM

0.1

1

10

100

ONE
PART
IN

10^8

10^7

10^6

10^5

10^4

UNCERTAINTY

SPECIAL–DESIGN TRANSFORMERS
10^4 rad/sec (1592 Hz)

INDUCTIVE
VOLTAGE
DIVIDERS
V_{ref} = 100 VOLTS

2 TO 10 kHz

PRESENT CAPABILITIES
PROPOSED OBJECTIVES

60 Hz TO 10 kHz

100 TO 1000 Hz

20 Hz TO 20 kHz

60 & 400 Hz

AC–DC VOLTAGE DIFFERENCE

20 Hz TO 20 kHz

5 Hz TO 50 kHz

60 Hz

VOLTAGE TRANSFORMER
V_{ref} = 100 VOLTS

400 Hz

VOLTS, V

10^{-3}

10^{-2}

10^{-1}

1

10^1

10^2

10^3

10^4

10^5

10^6

10^7

10^8

A–C Voltage and Voltage Ratio

F. L. HERMACH, F. R. KOTTER, W. W. SCOTT, JR., *Section Chiefs*

State of the art: A–c voltage measurements at power and audio frequencies are made with d–c potentiometers, ac–dc difference standards, and a–c voltage dividers. Estimated accuracies shown are for calibration of ideal reference standards (perfectly stable and unaffected by environment) and include 3 standard deviations plus estimated systematic error; accuracy of ratio V/V_{ref} is shown for ratio standards (transformers and dividers).

Industry needs: Developments in electronic standards demanding more accurate measurements. Ac–dc transfer standards needed for peak and average values as well as improved transfer standards for rms values. Better calibration accuracy for voltage transformers 60 to 400 Hz. Extension of low-voltage dividers to 10 kHz. USA moving to higher a–c transmission levels; need for calibration of transformers and capacitor voltage dividers.

Short-term objectives: Improved ac–dc transfer via thermal voltage converters and differential thermocouple principle. High-voltage transformers to within ± 10 ppm, 60 to 400 Hz. Low-voltage dividers 60 Hz to 10 kHz. Ac–dc transfer standards for peak and average values. Study of capacitor dividers.

ELECTRICAL POWER AND ENERGY   FLH 7/27/64

32
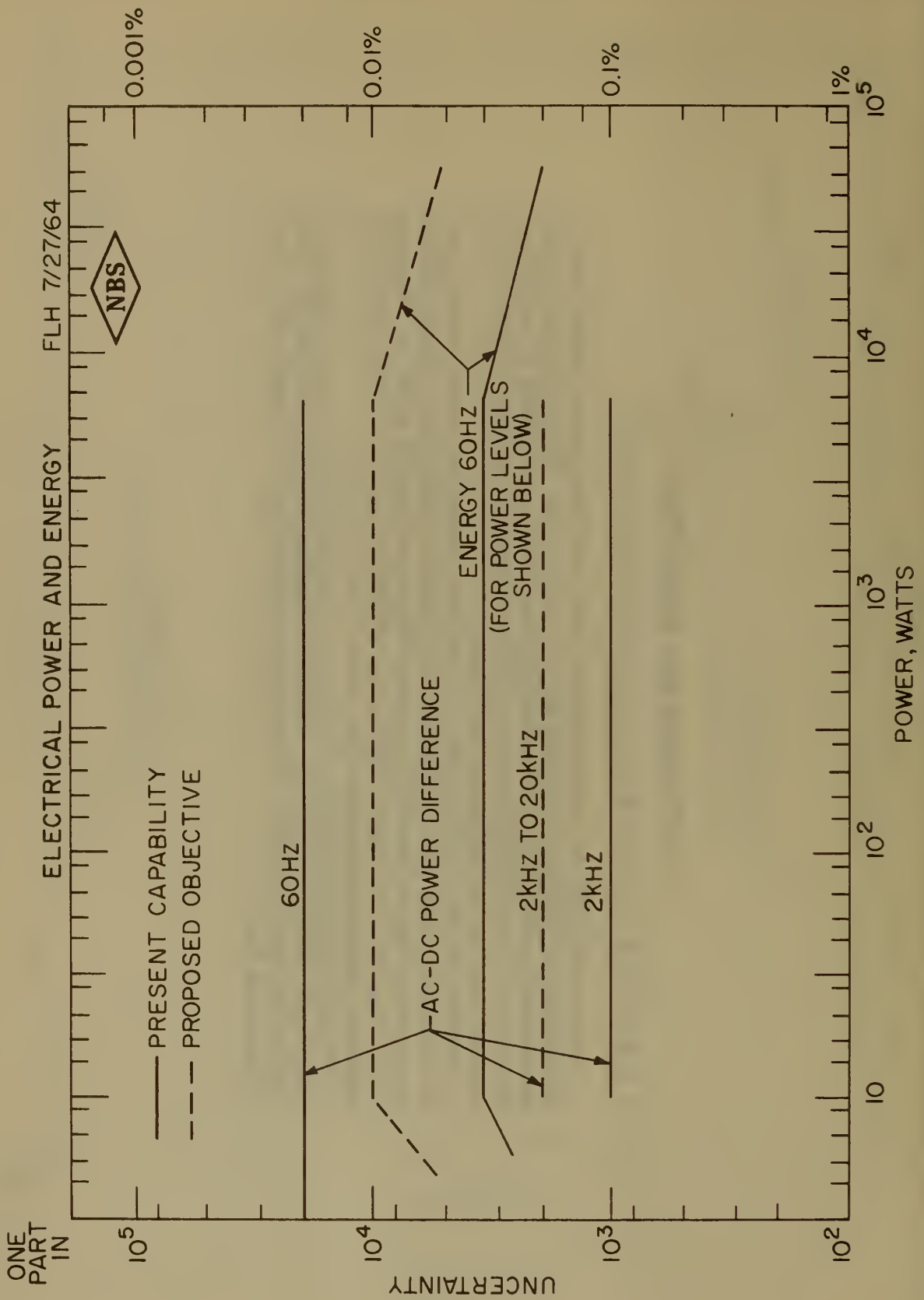
Power and Energy at Audio Frequencies

F. L. HERMACH, *Section Chief*

State of the art: NBS does not offer power calibration service; d–c power measurements are made with d–c potentiometer, standard cell, resistor, and voltage divider. Accurate a–c power measurements are made with ac–dc transfer wattmeter and these d–c standards; NBS determines only the ac–dc differences of such wattmeters. Energy measurements are made by comparison with a bank of four standard watthour meters, maintained as a working standard for energy and calibrated periodically with the NBS transfer wattmeter and NBS standard-frequency signals. Estimated accuracies shown are for calibration of ideal standards (perfectly stable and unaffected by environment), and include 3 standard deviations plus estimated systematic errors.

Industry needs: Improved accuracy of energy measurements at 60 Hz and extension to high frequencies. Power measurements above 1 kHz. Pulses of 5 kilojoules to develop very high temperatures for thermal research.

Short-term objectives: Ac–dc transfer measurement of power difference to within ±0.05 percent for 10 to 5000 W at 2 to 20 kHz. Energy measurements to within ±0.01 percent at 60 Hz. Develop capacitor discharge techniques for high-energy pulses of 300 kA at 100 kV for 5μ sec to 5 percent.

33

MAGNETIC FLUX DENSITY

34
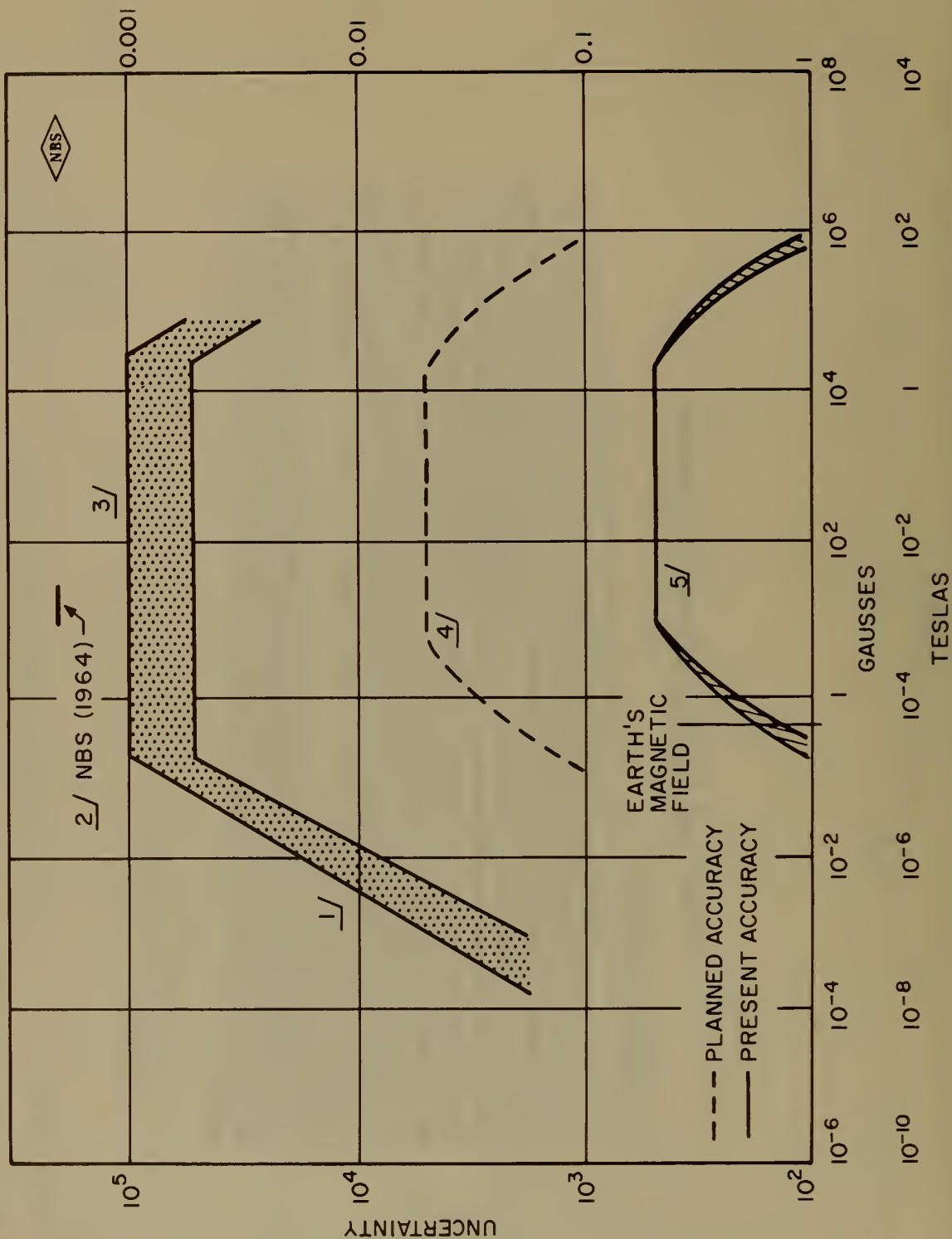
Magnetic Flux Density

I. L. COOTER, F. K. HARRIS, *Section Chiefs*

State of the art: Rubidium magnetometers are generally used for precision measurement of flux densities below 1×10^{-3} tesla.[1] A flux density of approximately 1×10^{-3} tesla was established in an air-cored solenoid at NBS in 1964.[2] From the measured coil constant and the accuracy of determining the current, the value of the flux density thus established is known with a probable error subjectively estimated to be ± 5 ppm. For precision measurements of fields greater than the earth's field, which is about 5×10^{-5} tesla, proton resonance magnetometers[3] are generally used.

Magnetic fields that are constant and homogeneous over a volume as large as the measuring probe may be measured by means of the rubidium and proton resonance magnetometers. However, most commercial and routine magnetic measurements use the search coil or Hall-effect methods.[5] These methods generally use the field of a permanent magnet as a reference or calibration standard. Permanent magnet standards vary widely in size, shape, air gap dimensions, guides and stop arrangement for the probe, temperature control, etc. Therefore, the value of the field in the gap of each standard is reported to an accuracy depending on its individual merit.

Industry needs: As permanent magnet standards are improved, more accuracy will be required.

Short-term objectives: Improvements in the method for determining the area-turns of search coils and in ballistic detection should result in increased accuracy of the measurement of flux densities for industrial applications. It is expected that the uncertainty of measuring flux density will be reduced to within ± 0.1 percent in the near future, and eventually to the planned accuracy line shown.[4]

References refer to correspondingly numbered areas on the chart.

IV. Charts for Electrical Quantities, 30 kHz to 1 GHz

HIGH-FREQUENCY CURRENT
(COAXIAL SYSTEMS)

REFERENCE STANDARDS
———— EXISTING CAPABILITY
━━━━ 5 YEAR OBJECTIVE

CALIBRATION SERVICE
———— EXISTING CAPABILITY
———— 5 YEAR OBJECTIVE

NON - NBS STATE OF THE ART

NBS

UNCERTAINTY (ONE PART IN)

CURRENT IN AMPERES

38

High-Frequency Current (Coaxial Systems)

N. V. FREDERICK, *Project Leader*, Standards

Existing capability: There are at present no reference standards for high-frequency current.

Five-year objective: Two approaches to the current-measurement problem have been established recently. One approach uses thin-film thermocouples and the other uses the electrodynamic ammeter. The Electro-Technical Laboratory of Japan has developed such an ammeter; the uncertainty of their measurements as compared to their thermo-ammeter corresponds to

$$s = \left[\frac{\sum\limits_{i=1}^{n} (E_i - \bar{E})^2}{n-1} \right]^{1/2}$$

$$\bar{E} = \frac{1}{n} \sum_{i=1}^{n} E_i, \, n = 9$$

$$E_i = \frac{i_i - i_i}{(I_i + i_i)/2}$$

I_i = the ith current indication of the electrodynamic ammeter

i_i = the ith current indication of the thermo-electric ammeter

I_i and i_i are read simultaneously.

In general the precision and absolute accuracy of the electrodynamic ammeter are limited by the ability to make precise mass, length, and time measurements, and to make accurate evaluations of the electric-field boundary-value problems presented by the geometry of the instrument. Serious limitations to precision and sensitivity are set by building vibrations and environmental thermal stability.

The instrument is expected to operate between 1 MHz and 1 GHz for currents of 1 to 100 amperes. It is hoped that thin-film thermocouples will supply a means of extending the measurement range below 1 ampere over the frequency range 1 to 300 MHz.

State of the art: The Japanese and Russian electrodynamic ammeters operate in the VHF and lower UHF bands at current around 100 amperes, giving uncertainties of about 1 part in 200 to 500

Reference:

"Research Highlights of Radio Standards and Measurements," *Electro Technical Laboratory of Japan.*

HIGH-FREQUENCY POWER
(CW COAXIAL SYSTEMS)

REFERENCE STANDARDS
    EXISTING CAPABILITY
    5 YEAR OBJECTIVE

CALIBRATION SERVICE
    EXISTING CAPABILITY
    5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

0.03-1000 MHz

0.1-1000 MHz

0.03-1000 MHz

10,30,100,200,300,400,500 MHz

10,30 MHz

POWER IN WATTS

UNCERTAINTY (ONE PART IN)

NBS

40
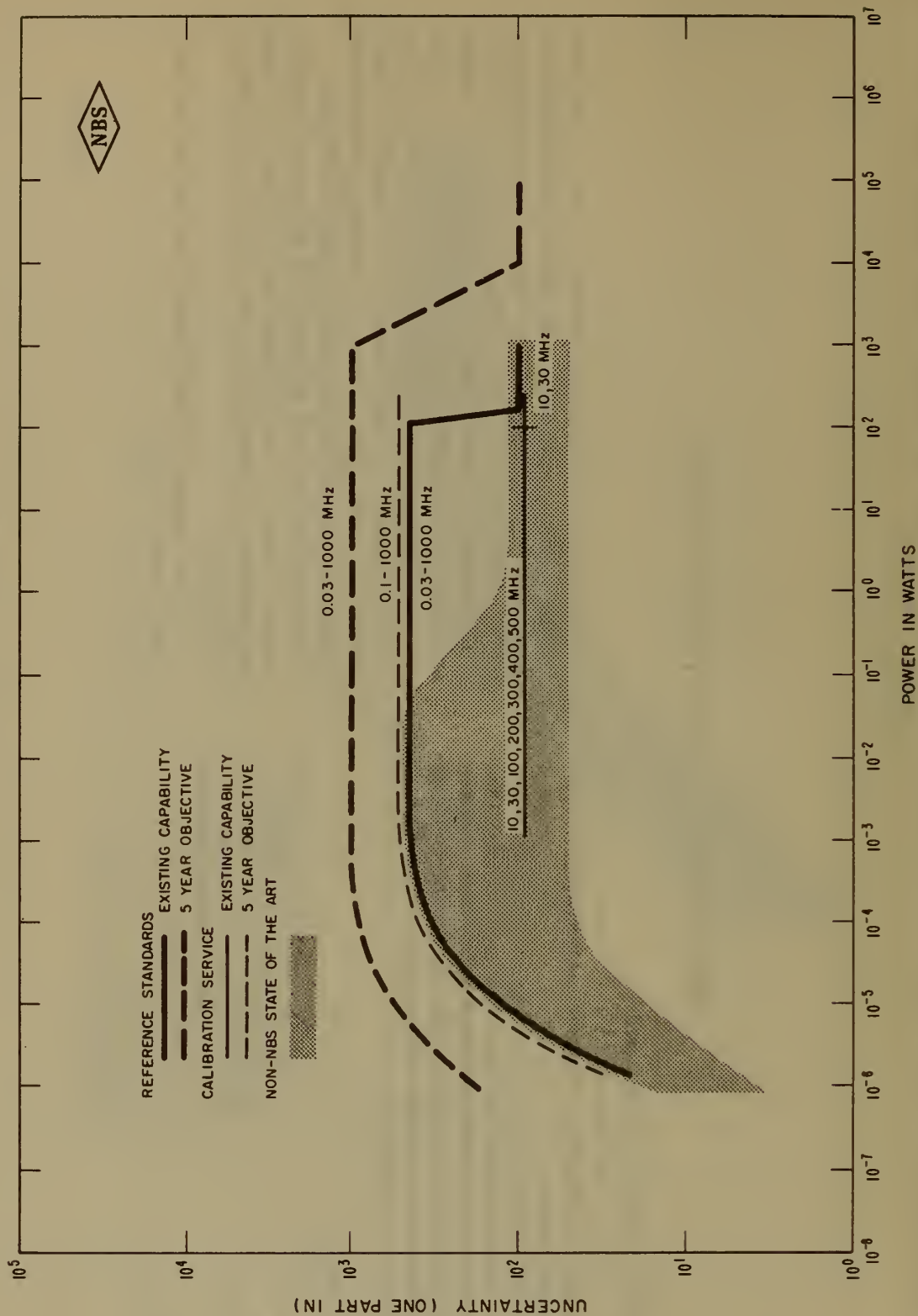
High-Frequency Power (CW Coaxial Systems)

P. A. HUDSON, *Project Leader*, Standards

I. S. BERRY, *Project Leader*, Dissemination

General: The term "uncertainty" as used in the chart refers to the closeness of NBS-measured values to the "true" value. In general, the assigned uncertainty is determined by adding together the magnitudes of individual uncertainties. Individual uncertainties are assigned from direct observations or by estimates of an upper limit. Verification is provided by comparison of two or more independent methods of measurement. Systematic errors arise due to thermal effects and impedance mismatch. At levels below 100 μW, measurement uncertainties increase rather rapidly due to thermal drifts and other causes.

Existing capability: Reference standards for high-frequency power measurement are of calorimetric type and have relatively long time constants (e.g., 20 to 30 min). The reference standards instruments and their ranges are as follows:

1. Bolometer bridge, 100 μW to 100 mW (calibrated against the dry load calorimeter).
2. Dry load calorimeter, 50 mW to 5 W.
3. Twin-joule flow calorimeter, 5 to 100 W.

All reference standards employ d-c substitution techniques.

It is possible to generate or standardize a low power level accurately (i.e., with uncertainty less than ± 1 percent) using directional coupler techniques, thus making it possible to calibrate microwatt and sub-microwatt power meters with acceptable uncertainties.

The range of the above standards also can be extended to higher power levels by use of directional couplers. The total range of interest extends from 10^{-8} to 10^5 W.

Working standards for performing HF power calibration measurements consist of calorimeters [1] and bolometer bridges [2, 3, 4] together with precision directional couplers.[5] These working standards are periodically intercompared with the previously mentioned reference standards.

Calibration services are presently available only for coaxial CW rf calorimeters having Type N connectors. The uncertainty stated on reports of calibration is 1 to 2 percent, depending upon the repeatability and SWR of the calorimeter undergoing calibration.
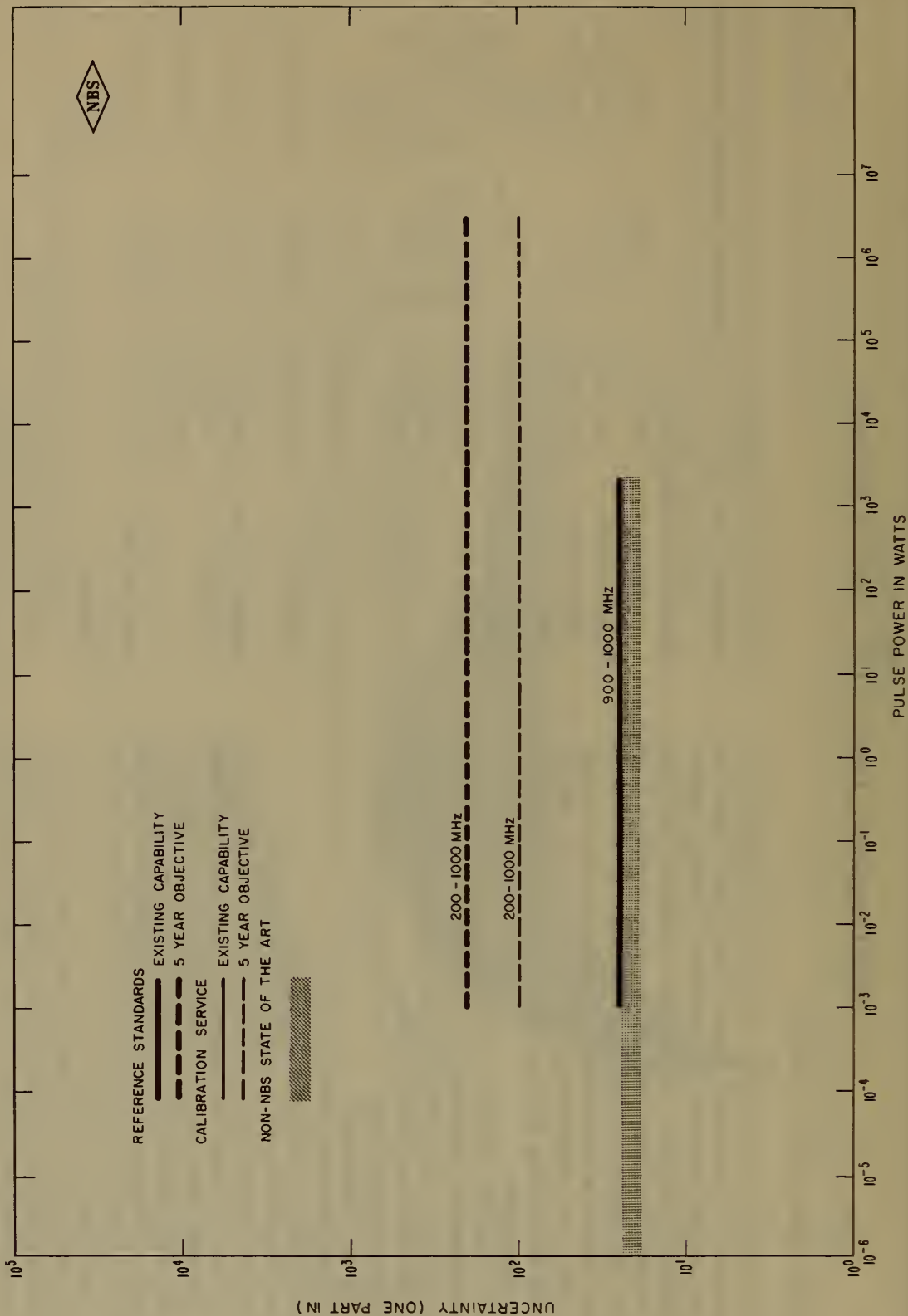
State of the art: Some of the information on which the state-of-the-art band is based follows:

Reference	Uncertainty	Range	Frequency
Required maximum measurement uncertainties based on calibration requirements.	1 part in 200	10^{-4}–10^{-2} W	100–300 MHz.
	1 part in 200	10^{-2} W	500 and 1000 MHz.
	1 part in 200	10^{-2} W	100, 300, 500, 1000 MHz.
	1 part in 100	10^{-3}–10^{-2} W	To 1000 MHz.
	1 part in 100	10^{-3}–10^{-2} W	220–250 MHz.
	1 part in 100	10–150 W	200, 300, 500 MHz.
	1 part in 50	8.10^{-3}–8 W	400 MHz.
Manufacturer	1 part in 100	5–125 W	30–1000 MHz.
Aerospace standards lab.	1 part in 50 to 70.	10^{-4}–10^{-2} W	10–1000 MHz.
	1 part in 100	1–50 W	100–1000 MHz.
Aerospace base	1 part in 30	20–100 W	100–500 MHz.

References:

[1] *Hudson, P. A., and C. M. Allred*, A dry, static calorimeter for RF power measurement, *IRE Trans. Instr.* I-7, 292 (1958).

[2] *U.S. Patent No. 2,883,620.*

[3] *U.S. Patent No. 2,997,652.*

[4] *Engen, G. F.*, A self-balancing d-c bridge for accurate bolometric power measurement, *J. Res. NBS* 59, 101 (1957).

[5] *Hudson, P. A.*, A precision RF power transfer standard, *IRE Trans. Instr.* I-9, 280 (1960).

HIGH-FREQUENCY POWER
(PULSE COAXIAL SYSTEMS)

REFERENCE STANDARDS

▬▬ EXISTING CAPABILITY
▬ ▬ 5 YEAR OBJECTIVE

CALIBRATION SERVICE

─── EXISTING CAPABILITY
─ ∙ ─ 5 YEAR OBJECTIVE

▨▨▨ NON-NBS STATE OF THE ART

200 - 1000 MHz

200 - 1000 MHz

900 - 1000 MHz

PULSE POWER IN WATTS

UNCERTAINTY (ONE PART IN)

⟨NBS⟩

High-Frequency Power (Pulse Coaxial Systems)

P. A. Hudson, *Project Leader*, Standards   P. A. Simpson, *Project Leader*, Dissemination

General: The term "uncertainty" as used in the chart refers to the closeness of NBS-measured values to the "true" value. In general, the assigned uncertainty is determined by adding together the magnitudes of individual uncertainties. Individual uncertainties are assigned from direct observations or by estimation of an upper limit. Verification is provided by comparison of two or more independent methods of measurement. Systematic errors arise due to thermal effects and impedance mismatch.

Existing capability: The reference standard is a sampling-comparison system employing a solid-state radio frequency switch. The measuring system is moderately complex. A measurement is accomplished by comparing peak pulse power to accurately known continuous wave power of the same frequency. The continuous wave power is measured in terms of d-c power.
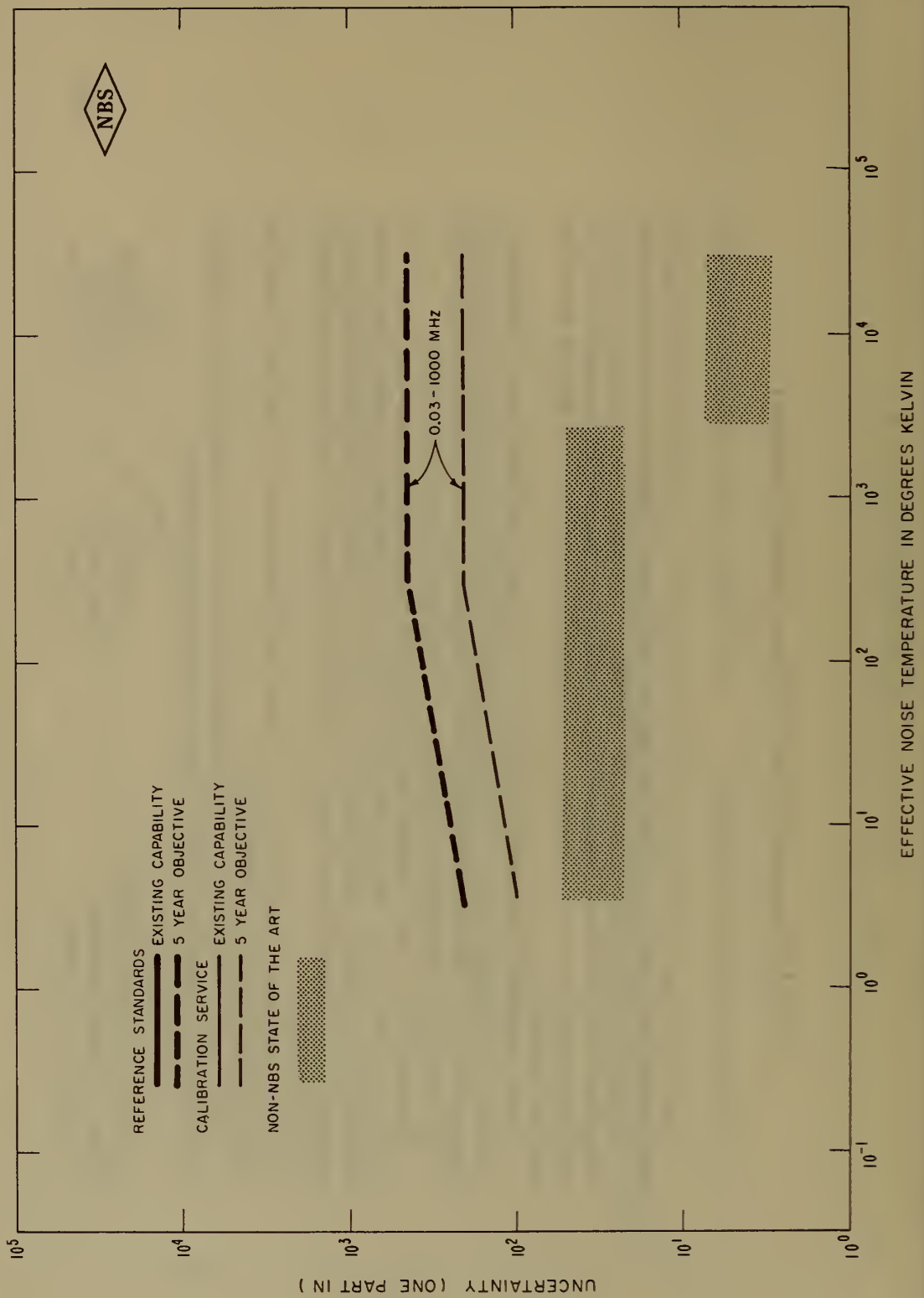
The range of the basic sampling-comparison method for peak pulse power measurement extends from 20 mW to 2 W. The upper limit is set by the power-handling capability of the switch. The total range of interest extends from 10^{-6} to 10^6 W. Measurement and standardizing can be accomplished throughout the total range by using the basic system in conjunction with calibrated directional couplers.

Five-year objective: A calibration service is now under development for peak pulse powers up to 5 kW at frequencies around 1000 MHz.

State of the art: The upper limit of the non-NBS state of the art coincides with the capability of the present U.S. reference standard. Other typical uncertainties follow:

Organization	Uncertainty	Range
Commercial standards laboratory	1 part in 20 to 30	1 μW–0.5 W.
Russian standards laboratory	1 part in 30	mW levels.
U.S. commercial instruments	1 part in 10	1 mW–2 kW.

43

HIGH – FREQUENCY NOISE
(COAXIAL SYSTEMS)

NBS

REFERENCE STANDARDS ━━━ EXISTING CAPABILITY
━━━ 5 YEAR OBJECTIVE

CALIBRATION SERVICE ━━━ EXISTING CAPABILITY
━━━ 5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

0.03 – 1000 MHz

UNCERTAINTY (ONE PART IN)

EFFECTIVE NOISE TEMPERATURE IN DEGREES KELVIN

44

High-Frequency Noise

M. G. ARTHUR, *Project Leader*, Standards   H. E. TAGGART, *Project Leader*, Dissemination

Existing capability: At present NBS has neither reference standards nor calibration service for random or impulse noise in the high-frequency range. Instruments and techniques for calibrating random noise generators and for measuring noise figure are under development. While noise has the units of power per unit bandwidth, it is often expressed as effective noise temperature, since the power per unit bandwidth is equal to Boltzmann's constant times the effective noise temperature.

Five-year objective: The uncertainties stated for the five-year objectives are for the worst-case situations; they are the sums of the magnitudes of individual contributions to uncertainty.

The lower temperature limit (approximately 4 °K) for the random noise standards is determined by cryogenic techniques which we intend to apply during the five-year period. The upper temperature limit (29,000 °K) is determined by the maximum ratings of present-day temperature-limited diode noise generators. Calibration service may cover temperature ranges outside these limits, but the need for this is not seen within this period.
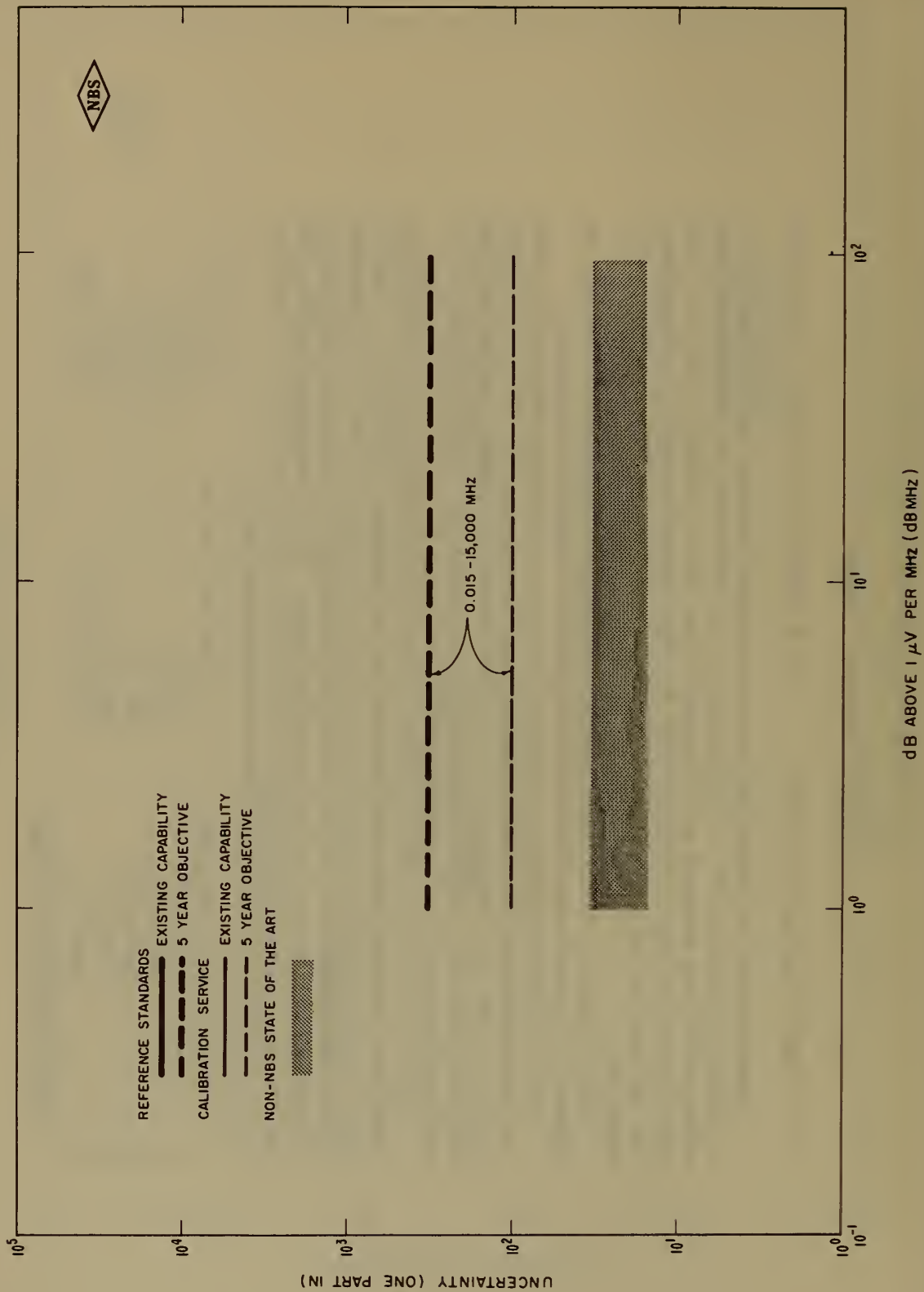
State of the art: The non-NBS state of the art bands are based upon the claims of commercial manufactures, statements from other laboratories, and the experience of NBS–BL staff. Since no national reference standard of noise power presently exists, these data are only approximate. Further, noise generators have not been built to cover continuously the temperature range indicated, but there appears to be no reason why this could not be done. The low-temperature section of the band pertains to thermal noise generators. The high-temperature section pertains to shot noise. Typical uncertainties determined by instrument manufacturers follow:

Manufacturer	Uncertainty	Effective noise temperature	Frequency range
I	1 part in 50	77 °K*	0–1 GHz.
I	1 part in 50	373 °K*	0–1 GHz.
II	1 part in 100	300 °K*	0–1 GHz.
II	1 part in 50	2200 °K*	0–1 GHz.
II	1 part in 8	600–29,000 °K**	1 MHz–1 GHz.

*Thermal noise generators, 50 ohms.
**Temperature-limited diode, 50 ohms.

45

IMPULSE SPECTRAL DENSITY

REFERENCE STANDARDS
EXISTING CAPABILITY
5 YEAR OBJECTIVE

CALIBRATION SERVICE
EXISTING CAPABILITY
5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

0.015 - 15,000 MHz

dB ABOVE 1 μV PER MHz (dB MHz)

UNCERTAINTY (ONE PART IN)

46

Impulse Spectral Density

M. G. ARTHUR, *Project Leader*, Standards   H. E. TAGGART, *Project Leader*, Dissemination

Five-year objective: While impulse spectral density has the units of power per unit bandwidth, it is common practice to express it in decibels above 1 μV per megahertz. An impedance of 50 ohms is assumed. Standards and calibration service for impulse noise will not be pursued until late in the five-year period. Therefore, all information on these quantities is tentative at this time and will be revised as the need demands.

Non-NBS state of the art: Measurement uncertainties claimed by instrument manufacturers are ± 0.5 dB over a range of 0 to 100 dB at any frequency from 10 kHz to 10 GHz. Requirements stated by an aerospace company are for a range of 0 to 100 dB with uncertainties of 0.25 dB from 10 kHz to 1 GHz, and 0.5 dB from 1 to 10 GHz.

HIGH-FREQUENCY VOLTAGE
(CW COAXIAL SYSTEMS)

48
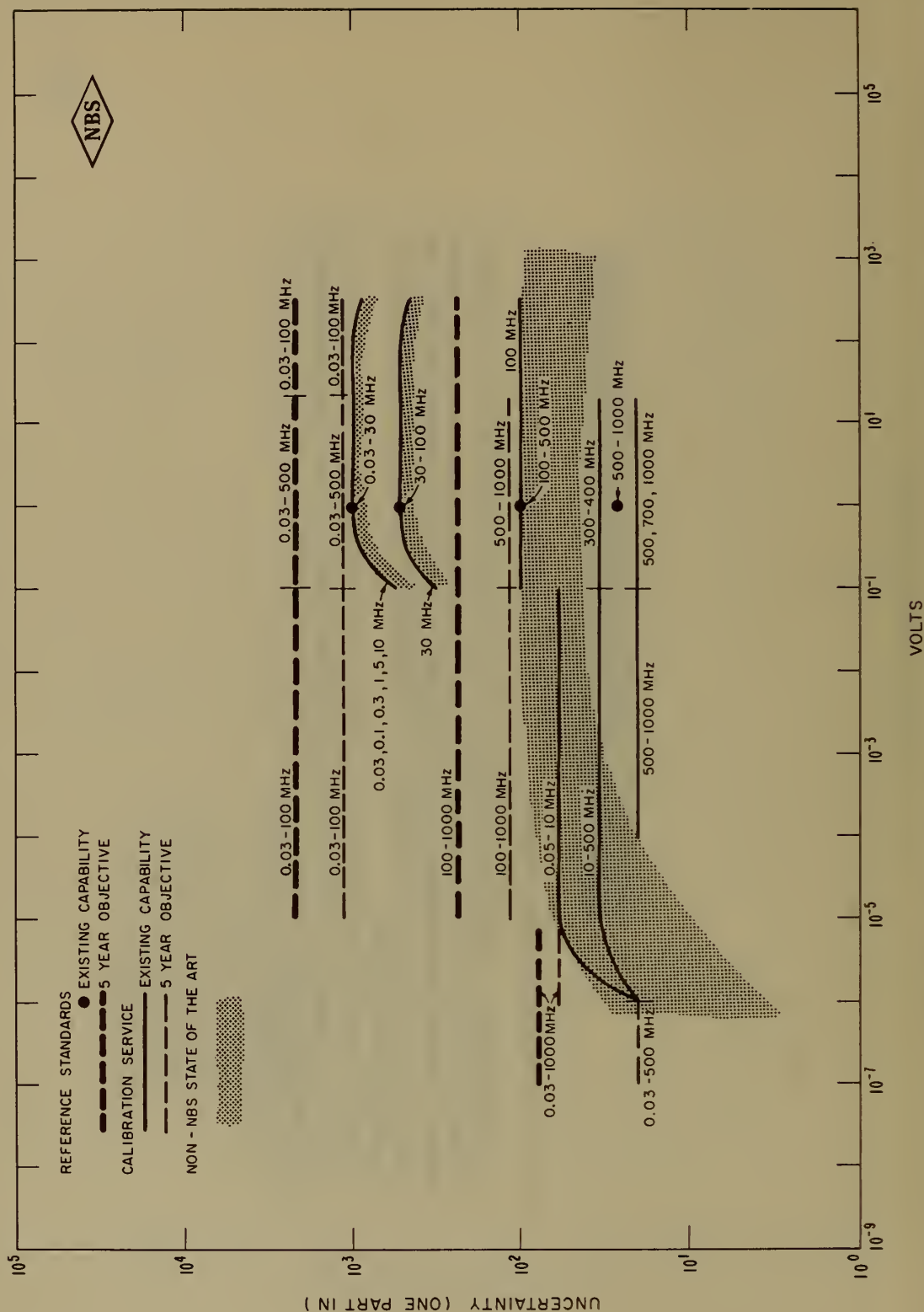
High-Frequency Voltage (CW Coaxial Systems)

M. C. SELBY, *Project Leader*, Standards   F. X. RIES, *Project Leader*, Dissemination

General: The stated uncertainty is the estimated maximum deviation from an algebraic mean based on (1) agreement between independent analytically sound methods, (2) reproducibility, and (3) a certain safety factor.

The major existing limitations on accuracy are (1) the dynamic instability of the electronic equipment, e.g., power sources, and (2) ambient temperature variations.

Existing capabilities: The reference standards and instruments used to cover the ranges shown are as follows:

Thermal voltage converter: 0.1 to 300 V, 30 kHz to 30 MHz
Voltage bridges: 20 mV to 1.2 V, 30 kHz to 1000 MHz
Cathode ray technique: 5 to about 250 V, 30 kHz to 40 MHz
Voltage bridge and attenuator: 1 to about 250 V, 30 kHz to 100 MHz; 1 to 100 V, 30 kHz to 300 MHz
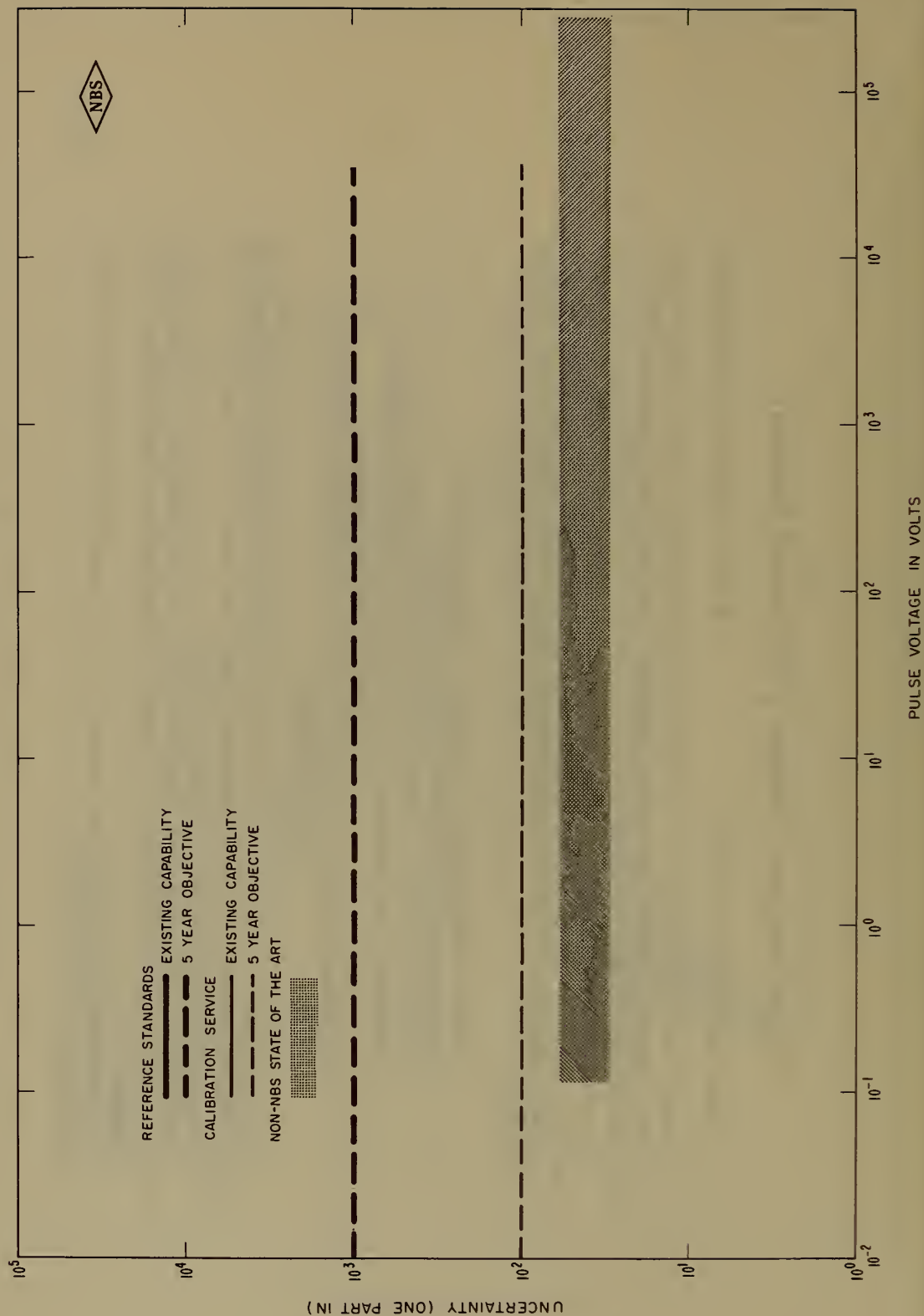Micropotentiometers: 0.1 to 10^5 μV, 30 kHz to 700 MHz; 10 to 10^5 μV, 700 to 1000 MHz

Five-year objective: The basic principles of existing techniques seem applicable to the nonexisting ranges, but the instrumentation and elimination of additional sources of error (negligible at lower frequencies) will require considerable thought and effort.

State of the art: The state of the art bands are based on (1) NBS capability, (2) claims of other laboratories, both foreign and domestic, and (3) claims and specifications of commercial instruments.

Reference:
IRE Technical Committee Report on the State-of-the-Art of Measuring Sine-Wave Unbalanced RF Voltage, *Proc. IRE 51, No. 4, 575–580 (Apr. 1963).*

HIGH-FREQUENCY VOLTAGE
(PULSE COAXIAL SYSTEMS)

REFERENCE STANDARDS
——— EXISTING CAPABILITY
– – – 5 YEAR OBJECTIVE

CALIBRATION SERVICE
——— EXISTING CAPABILITY
– – – 5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

PULSE VOLTAGE IN VOLTS

UNCERTAINTY (ONE PART IN)

50

High-Frequency Voltage (Pulse Coaxial Systems)

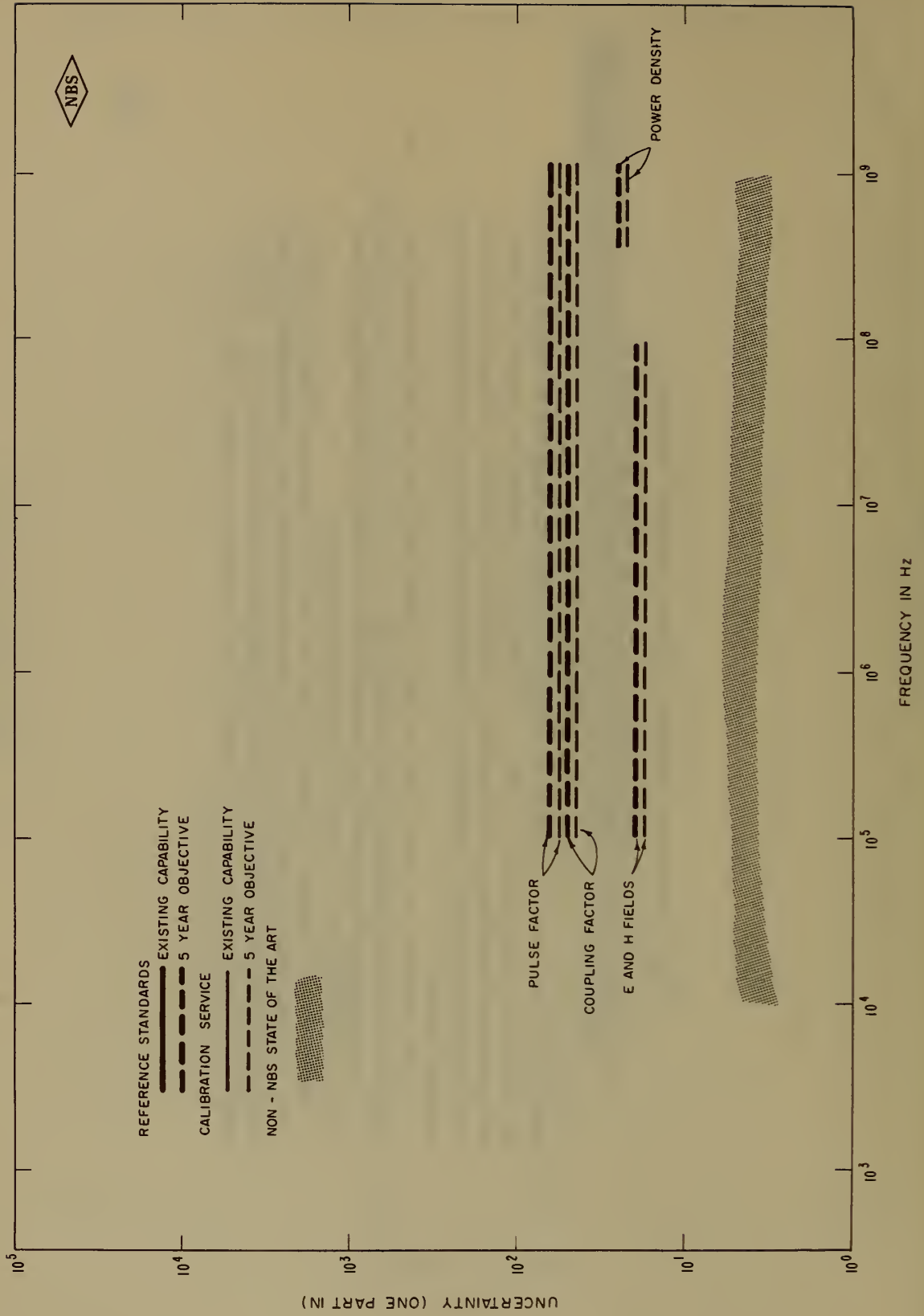P. A. HUDSON, *Project Leader*, Standards   P. A. SIMPSON, *Project Leader*, Dissemination

General: The term "uncertainty" as used in the chart refers to the closeness of NBS-measured values to the "true" value. In general, the assigned uncertainty is determined by adding together the magnitudes of individual uncertainties. The individual uncertainties are assigned from direct observations or by estimation of an upper limit. Verification is provided by comparison of two or more independent methods of measurement. Systematic errors arise due to thermal effects and impedance mismatch.

Existing capability: At present, NBS has only a limited service for the ratio factor of pulse voltage dividers under single-pulse conditions (see p. 29).

Five-year objective: It is expected that standards will be developed for the measurement of pulse risetimes and other quantities needed in fast-pulse instrumentation.

State of the art: The non-NBS state of the art band is derived from manufacturers' advertisements, accuracies quoted in scientific papers, and direct communications. Uncertainties of 1 part in 30 to 50 for peak pulse voltages of 1 to 350 kV are needed for linear accelerator work. U.S. commercial instrument manufacturers claim 1 part in 20 to 50 for peak pulse voltages of 0.1 to 1 kV.

HIGH-FREQUENCY FIELD STRENGTH, NEAR-FIELD REGION

REFERENCE STANDARDS
EXISTING CAPABILITY
5 YEAR OBJECTIVE

CALIBRATION SERVICE
EXISTING CAPABILITY
5 YEAR OBJECTIVE

NON - NBS STATE OF THE ART

PULSE FACTOR
COUPLING FACTOR
E AND H FIELDS
POWER DENSITY

UNCERTAINTY (ONE PART IN)

FREQUENCY IN Hz

52

High-Frequency Field Strength (Near-Field Region)

F. M. Greene, *Project Leader*, Standards

H. E. Taggart, *Project Leader*, Dissemination

General: The near-field region of a simple transmitting antenna is here considered to extend out to a distance of about one wave-length from the antenna.

Calibrations are made in terms of sinusoidally time-varying (CW) electric or magnetic field components parallel to the axis of the antenna.

Power density represents average power flow at any point in the field, i.e., the real part of the Poynting vector.

The pulse factor is the quantity by which the CW calibration factor is multiplied to obtain the pulse calibration, for specified pulse characteristics.

The coupling factor is the attenuation introduced between the measuring antenna and the receiver to permit a high-level field measurement in terms of a low-level calibration.

Existing capabilities: There are no existing NBS capabilities in the near-field region areas listed.

Five-year objectives: The proposed uncertainty of the *E* and *H* field standards (five-year objective) is 1 part in 20, or 5 percent, as indicated by the ordinate of the chart. The uncertainty statements represent our best estimate of the present needs that can be realized in the time specified. The anticipated sources of systematic errors are similar to those listed for the loop and dipole antenna standards under *High-Frequency Field Strength.* The proposed frequency range

for *E* and *H* field standards is shown as 0.1 to 100 MHz. Measurements at lower frequencies than this may be difficult to achieve because of greater sensitivity requirements for the *H* field and because of a higher impedance requirement on voltmeters to minimize loading of short dipoles. There may be difficulty in measuring *H* fields at frequencies higher than 100 MHz because of increasing uncertainty in the frequency corrections for loop antennas. Power-density standards are not shown below 300 MHz because of the uncertainty of the requirements at the present time. We anticipate an increasing complexity in measuring power density with decreasing frequency in the near zone. Also, the actual usefulness of power-density measurements at these lower frequencies has not been fully analyzed. Pulse-factor and coupling-factor standards are shown over the range from 0.1 to 1000 MHz to complement the *E, H,* and power-density standards. The proposed calibration uncertainty is essentially the same as that of the standards, and is as shown on the chart. The proposed frequency range of calibration is essentially the same as that for the standards as that outlined above.

State of the art: The present state of the art is shown by the shaded area on the chart. It is an estimate based entirely on discussions with personnel of other laboratories, and has an uncertainty of the order of 2 to 3 dB. Field strength is often stated as a coefficient or gain, i.e., a numeric.

53

HIGH-FREQUENCY FIELD STRENGTH
(ANTENNA COEFFICIENT)

54
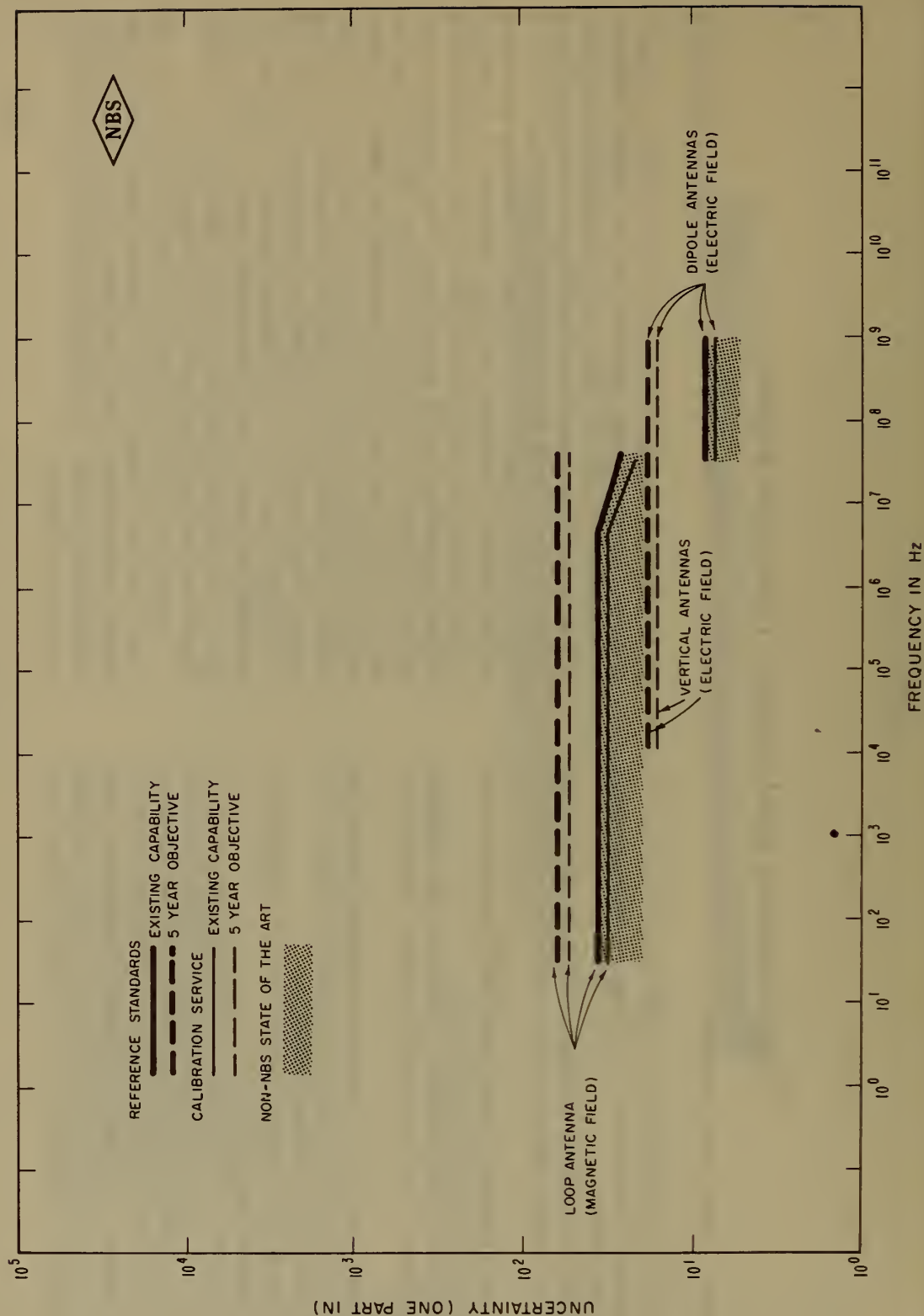
High-Frequency Field Strength (Antenna Coefficient)

F. M. Greene, *Project Leader*, Standards   H. E. Taggart, *Project Leader*, Dissemination

General: Antenna coefficients are determined for the types of antennas discussed below, in the frequency range 30 Hz to 1000 MHz. In general, the *antenna coefficient* is a *calibration factor*, i.e., a *proportionality constant*, by which the indication of the field-strength meter must be multiplied to obtain the magnitude of the unknown field strength, E or H, parallel to the axis of the antenna at a given frequency. Some instruments are direct-reading, so that the *antenna coefficient* is essentially unity. In other types of instruments, the coefficient can be expressed either as a factor or in decibels, relative to an arbitrary reference incorporated in the instrument design. Calibrations are made for sinusoidally time-varying (CW) fields only.

Field-strength meters employing shielded loop antennas are used over the frequency range from 30 Hz to about 30 MHz and measure magnetic field strength, H. However, it is standard practice to express the calibration in terms of the electric field, E, that would exist in the case of a free-space plane wave ($E = 120\pi\, H$).

At frequencies in the range 30 to 1000 MHz, field-strength meters generally employ half-wave dipoles. These are calibrated in terms of the component of electric field, E, parallel to the axis of the dipole.

Certain types of field-strength meters use a short (vertical) rod antenna, working against the metal case of the instrument, to measure vertically polarized electric field strength. However, NBS has no facilities, at present, for calibrating this particular type of antenna.

The "*standard-antenna*" method is used to evaluate the component of field strength parallel to the axis of a receiving antenna in terms of (a) the voltage induced in the antenna by this component of the field, and (b) the dimensions and form of the antenna.

The "*standard-field*" method is used to generate a known field in terms of (a) the current flowing at reference terminals of the antennas, (b) the dimensions and form of the transmitting antenna, (c) the distance to the point at which the field is to be evaluated, and (d) the effect of the ground.

Existing capability: The available accuracy of the reference standards and calibration services is given by the ordinate. In the case of the existing reference standards for loop antennas below 5 MHz, e.g., the uncertainty shown is 1 part in 30, or 3 percent. In general, the specified uncertainty in the reference standards is twice the average percentage difference between the "*standard-antenna*" and "*standard-field*" techniques of evaluation. The principal systematic errors involved in existing standards result from uncertainties in the following:

(a) *Loop antennas:* current distribution, proximity effects, linear dimensions, distributed capacitance.

(b) *Dipole antennas:* current distribution, end effect, crystal voltmeter, ground effect, linear dimensions.

As stated above, the uncertainty in the field-strength standards is determined from the difference between the *standard-antenna* and *standard-field* techniques of evaluation. However, in the normal calibration of field-strength meters it is often more convenient or practical to use one technique than the other. For example:

(a) The *standard-field* technique is used below 30 MHz for the calibration of loop antennas.

(b) Above 30 MHz the *standard-antenna* technique is used for calibrating dipole antennas.

In (a), the sensitivity and accuracy of the standard-antenna technique are not sufficient at present for use in regular calibrations. In (b), the uncertainty and nonuniformity of the ground properties, and difficulties in accurately determining them, preclude the use of the standard-field technique above 30 MHz, except as an intercomparison with the standard-antenna technique at spot frequencies, during initial development of the standards.

The accuracy available in calibration is as shown on the accompanying chart.

Loop antenna standards and calibration services are not available above 30 MHz for the following reasons: (a) uncertainty of frequency corrections, (b) uncertainty in evaluating proximity effects, and (c) no demand for service for these reasons.

Dipole antenna standards and calibration are not available below 30 MHz because of (a) cumbersome length of self-resonant antennas, (b) uncertainty in evaluating close electrical proximity to the ground, and (c) no demand for service for these reasons.

Five-year objectives: The planned improvement in reference standards and calibration service in the next five years as is follows:

(a) *Loop antennas* (magnetic field). It is proposed to reduce the uncertainty from 3 percent to 2 percent over the range from 30 Hz to 5 MHz; and from 5 percent to 2 percent over the range 5 to 30 MHz.

(b) *Dipole antennas* (electric field). There is a definite need for reduction of uncertainty in this area over the frequency range 30 to 1000 MHz. It is proposed to reduce the uncertainty from 12 to 6 percent over the next five years.

State of the art: The state of the art is shown by the shaded area on the chart. It is based on considerations of (a) NBS capability, (b) roundrobin calibrations of instruments performed by NBS and other leading laboratories, and (c) claims made by other standards laboratories, both foreign and U.S., and both government and private.

The ranges covered are as follows:

30 Hz to 30 MHz. Standard-field technique for calibrating loop antennas (magnetic field). Accuracy: 30 Hz to 5 MHz—3 percent; 5 MHz to 30 MHz—5 percent.

30 to 1000 MHz. Standard-antenna technique for calibrating dipole antennas (electric field). Accuracy—12 percent.

The accuracy of the loop-antenna standards is degraded to 5 percent between 5 and 30 MHz from the 3-percent figure that applies to frequencies below 5 MHz. This is because of the increasing uncertainty in evaluating the frequencies above 5 MHz. The limits of applicability of particular operating techniques are described above. In addition, the use of dipole techniques appears to have an upper frequency limit of about 1000 MHz. This is because of the difficulty in accurately measuring current and voltage (as such, necessary to this technique) at frequencies much above 1000 MHz.

HIGH-FREQUENCY RESISTANCE (0.03 TO 10 MHz)
LOW-PHASE-ANGLE RESISTORS

56
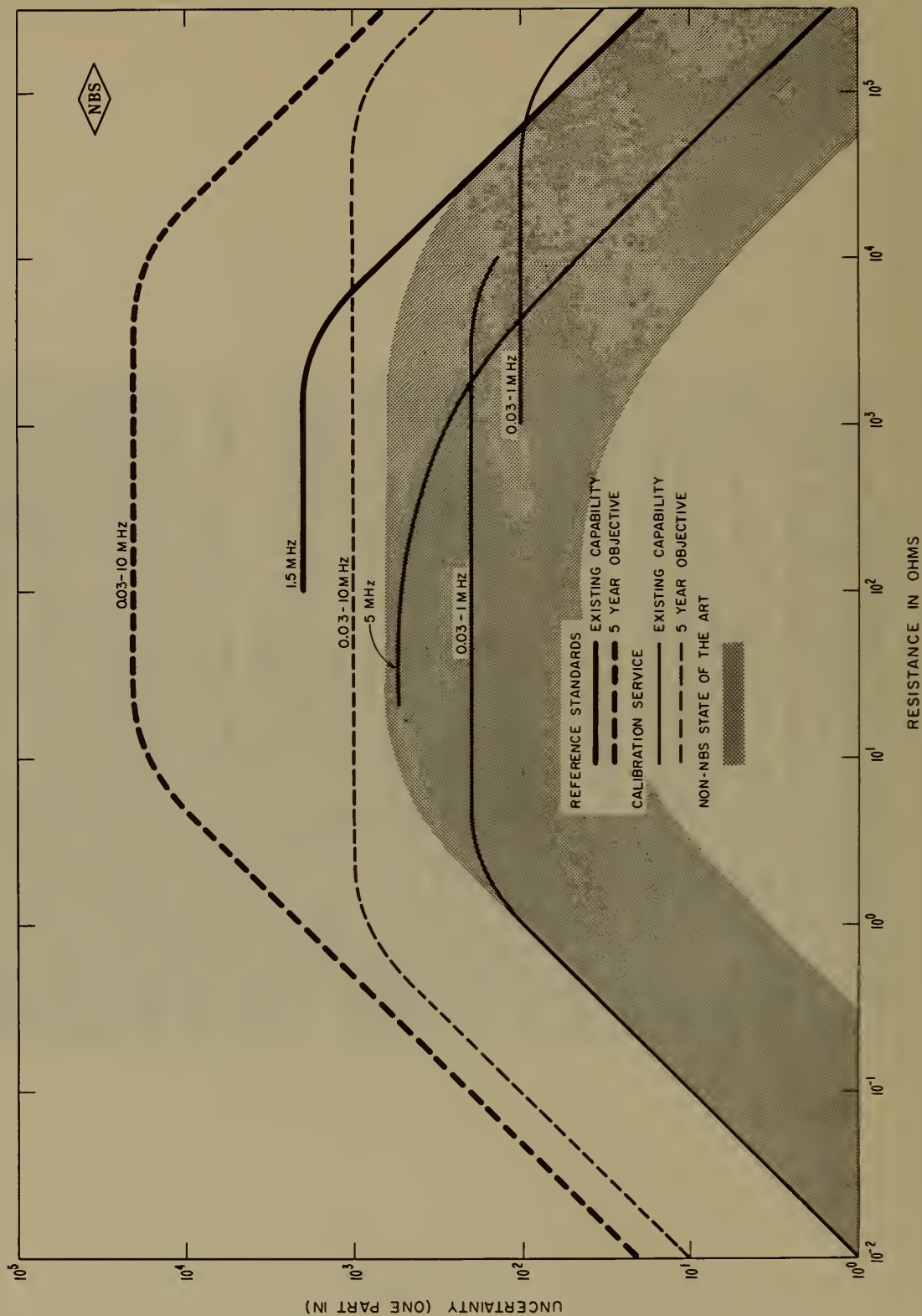
High-Frequency Resistance

A. E. HESS, *Project Leader,* Standards   R. N. JONES, *Project Leader,* Dissemination

General: The limiting factors in high-frequency measurements are as follows: The accuracy of low resistance measurements is limited by the uncertainty in connector contact resistance, about 1mΩ, and by the uncertainty in series inductance, about 1 pH, as well as by loss of measuring resolution, about 1 ppm at 100Ω.

The accuracy of high resistance measurements is limited by measuring instrument resolution and by the uncertainty of shunt capacitance, about 1 fF.

Existing capability: The following three instruments are used to determine HF resistance:

1. Woods twin-T bridge: 5 to 250 MHz, 25 to 10,000 ohms.

2. NBS self-calibrating twin-T bridge: 1.5 MHz, 100 to 10,000 ohms.

   Both instruments are used to measure conductance (resistance) in terms of capacitance, thus are limited by the accuracy to which high-frequency capacitance is known.

3. A 2½-meter slotted line: 50 to 1000 MHz, 1 to 2500 ohms.

   Resistance may be determined from slotted-line measurements of standing wave ratio in terms of the characteristic impedance of the line and phase shift.

The value of resistance from 30 kHz to 1.5 MHz is in part determined by interpolation between the measured d-c and rf values.

For calibration service, calibrated Maxwell impedance bridges and ratio admittance bridges are used in addition to the previously mentioned instruments. High-precision coaxial connectors are used to obtain the lowest uncertainty of resistance measurements.

(continued)

HIGH-FREQUENCY RESISTANCE (10 TO 1000 MHz)
LOW-PHASE-ANGLE RESISTORS

58
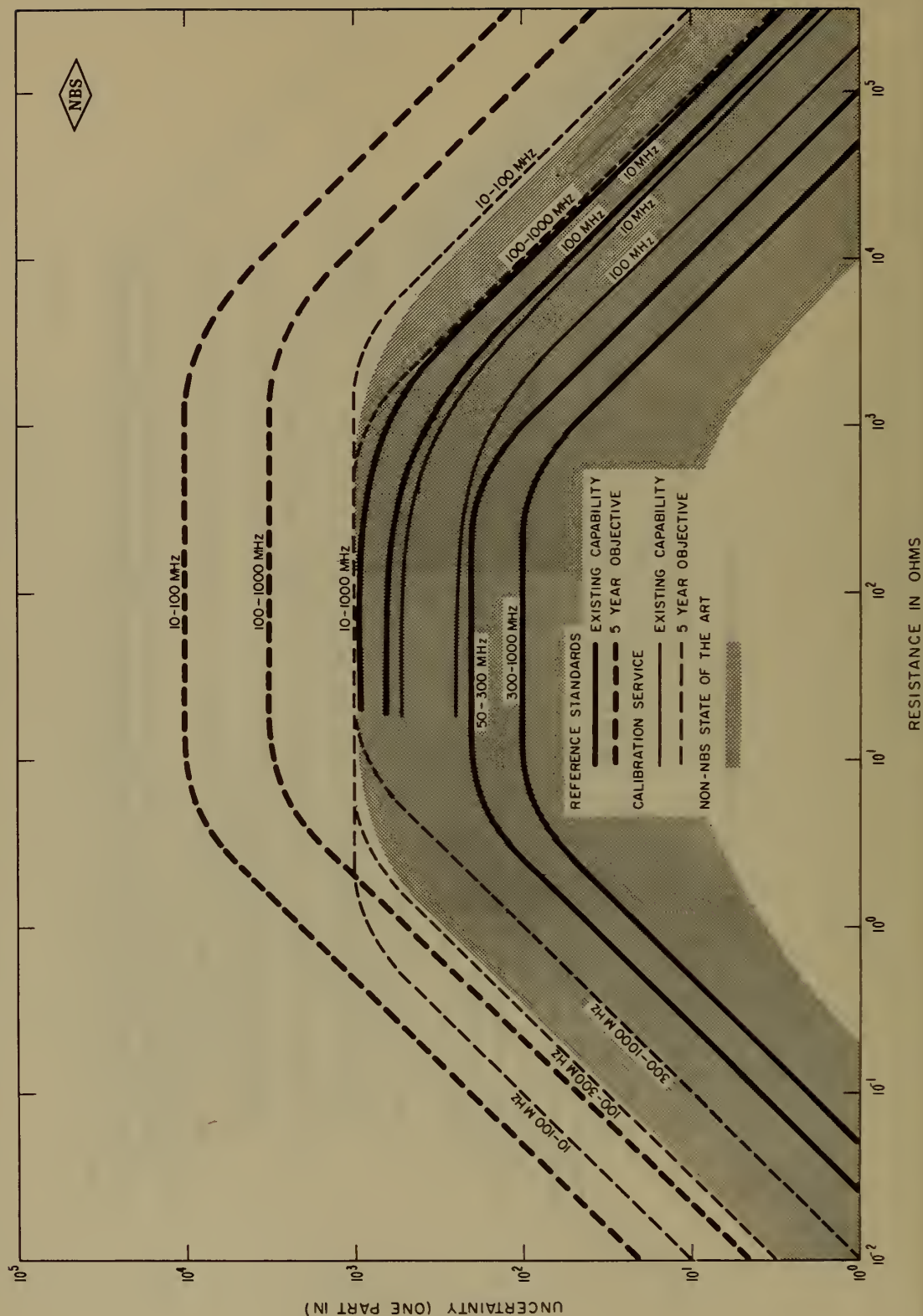
State of the art: The upper limits of the non-NBS state of the art bands indicate the least reported resistance-measuring uncertainty at the lower frequencies. The lower limits of the bands indicate the increased uncertainty in resistance measurement at the higher frequencies. Typical data used in determing the state of the art follow:

Organization	Uncertainty	Range (ohms)	Frequency (MHz)
Military standards laboratory, England.	1 part in 300–900	20–300	3–300.
Manufacturer I	1 part in 50–100	50–100	0.05–5.
Manufacturer I	1 part in 40–800	10–1000	0.4–60.
Manufacturer I	1 part in 10–25	3–700	25–1500.
Manufacturer II	1 part in 30	2–2000	50–500.
Manufacturer III	1 part in 20–40	15–1000	0.5–250.
Manufacturer IV	1 part in 50–100	1–100,000	0.015–5.
Manufacturer V	1 part in 30–50	250–25,000	1–50.
Manufacturer's standards laboratory.	1 part in $500+0.05\Omega$	0–1300	0.5–20.
Aerospace standards laboratory.	1 part in 400	10	0.1–50.

HIGH-FREQUENCY CAPACITANCE (0.03 TO 10 MHz)
(LOW-LOSS CAPACITORS)

60
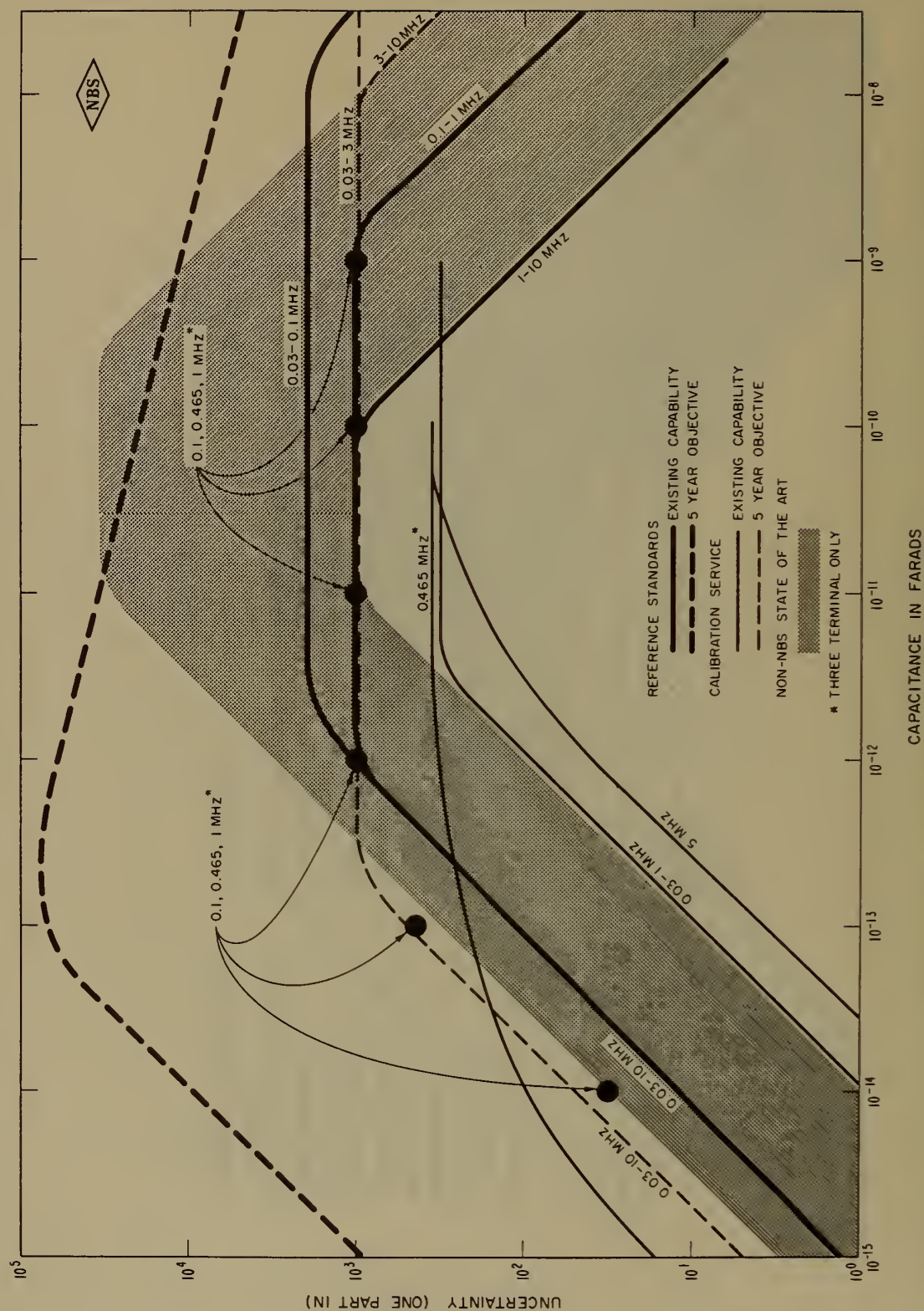
High-Frequency Capacitance

L. E. HUNTLEY, *Project Leader*, Standards   R. N. JONES, *Project Leader*, Dissemination

General: The chart shows the uncertainty in measuring capacitance at various frequencies. In most cases, two like capacitors can be compared with a precision which is one or two orders of magnitude greater than the accuracy which may be assigned to the measurement of either. At the lower frequencies (below about 50 MHz), the accuracy obtainable is limited primarily by the accuracy with which frequency corrections to capacitance standards can be evaluated. At frequencies above 50 MHz, where slotted-line measurements are practical, the accuracy obtainable depends upon the quality of the slotted line. At any frequency, the lowest two-terminal capacitance which can be measured to a given accuracy is determined by the connector uncertainty, which in the case of capacitors equipped with precision coaxial connectors is the uncertainty in the fringe capacitance or other reference capacitance.

Existing capability: The low-capacity limits of the curves are determined by the uncertainty of the reference capacitance (about 1 fF). The high-capacity limits of the curves are determined by the uncertainty in frequency corrections. Above 100 MHz, additional restrictions are encountered due to errors associated with slotted-line measurements.

State of the art: The non-NBS state of the art bands apply only to the measurement of two-terminal capacitors, since the problems encountered in measuring three-terminal capacitors are somewhat different. (The calibration service offered for three-terminal capacitors is about at the level of the state of the art in that area.) The upper limits of the state of the art bands represent the lower frequencies, while the lower limit represents the higher frequencies. Typical data used to determine the state of the art follow:

(continued)

HIGH-FREQUENCY CAPACITANCE (10 TO 1000 MHz)
(LOW-LOSS CAPACITORS)

62
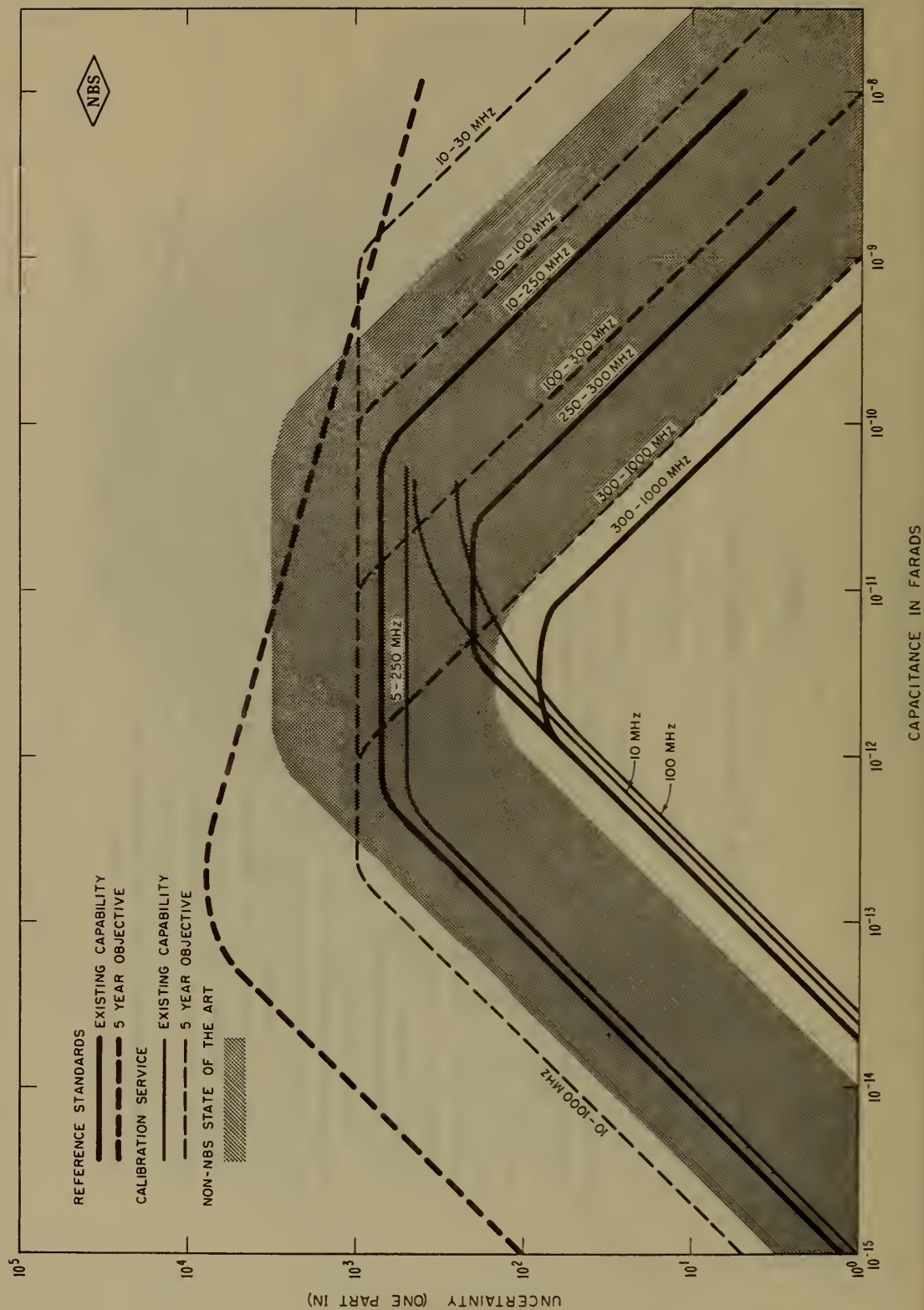
Organization	Uncertainty	Capacitance range	Frequency
University laboratory	1 part in 4000	200 pF (3-terminal)	1 MHz.
University laboratory	1 part in 5000	400 pF (3-terminal)	1 MHz.
University laboratory	1 part in 500	200 pF	1 MHz.
Military standards laboratory	0.001 pF	"All practical cases"	5–50 MHz.
Commercial stds. laboratory	1 part in 1600	92 pF	1 MHz.
Commercial stds. laboratory	0.01 pF	to 200 pF	10 MHz.
Instrument manufacturer	1 part in 1000+1 pF	100–1150 pF	1 MHz.
University laboratory	1 part in 800	40 pF (3-terminal)	50 MHz.
University laboratory	1 part in 800	80 pF (3-terminal)	50 MHz.
University laboratory	1 part in 900	40 pF	50 MHz.
Commercial stds. laboratory	1 part in 1000	130 pF	20 MHz.
Commercial stds. laboratory	0.01 pF	to 200 pF	10 MHz.

HIGH-FREQUENCY INDUCTANCE (O.O3-10 MHz)
(LOW-LOSS INDUCTANCE)

64
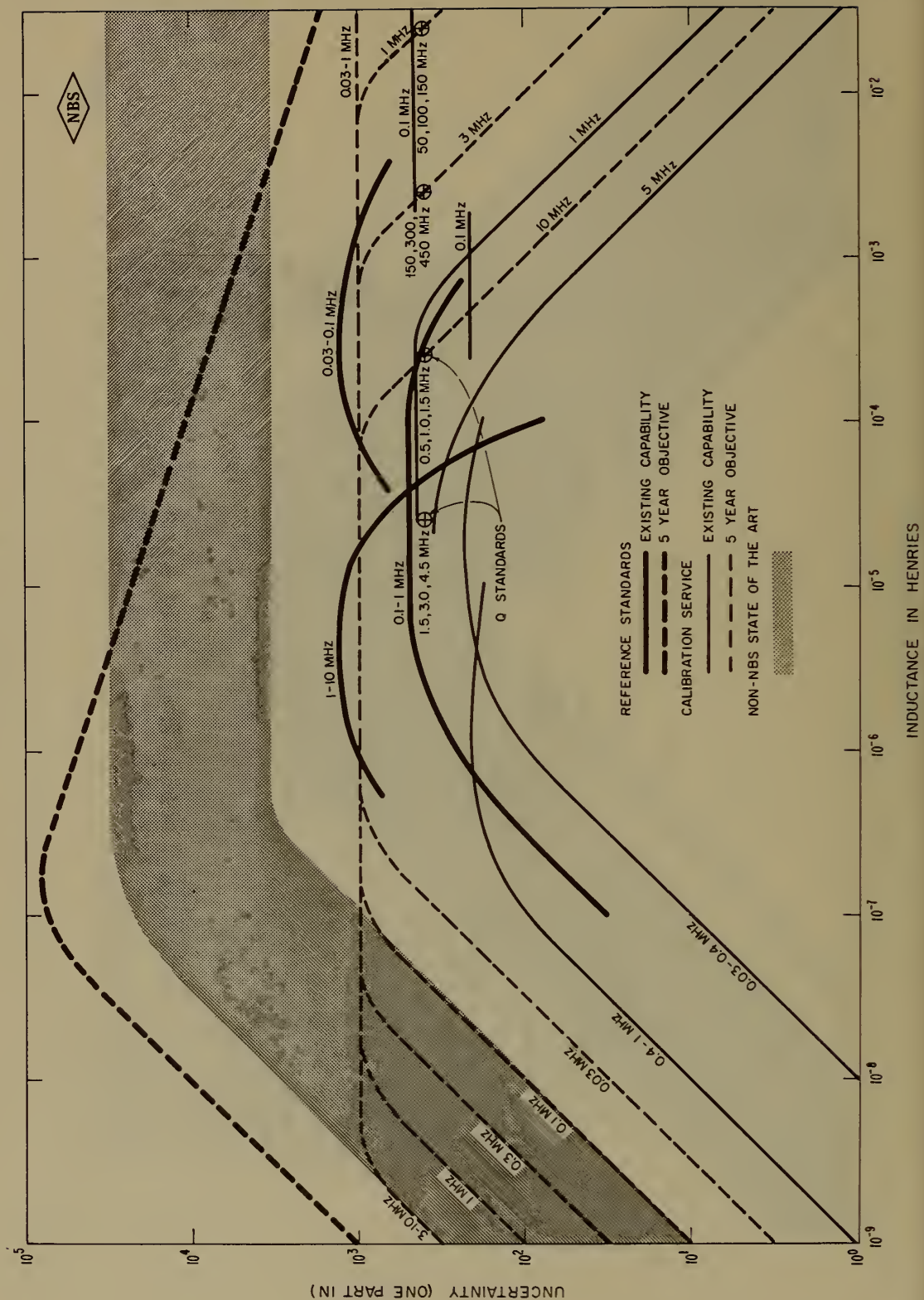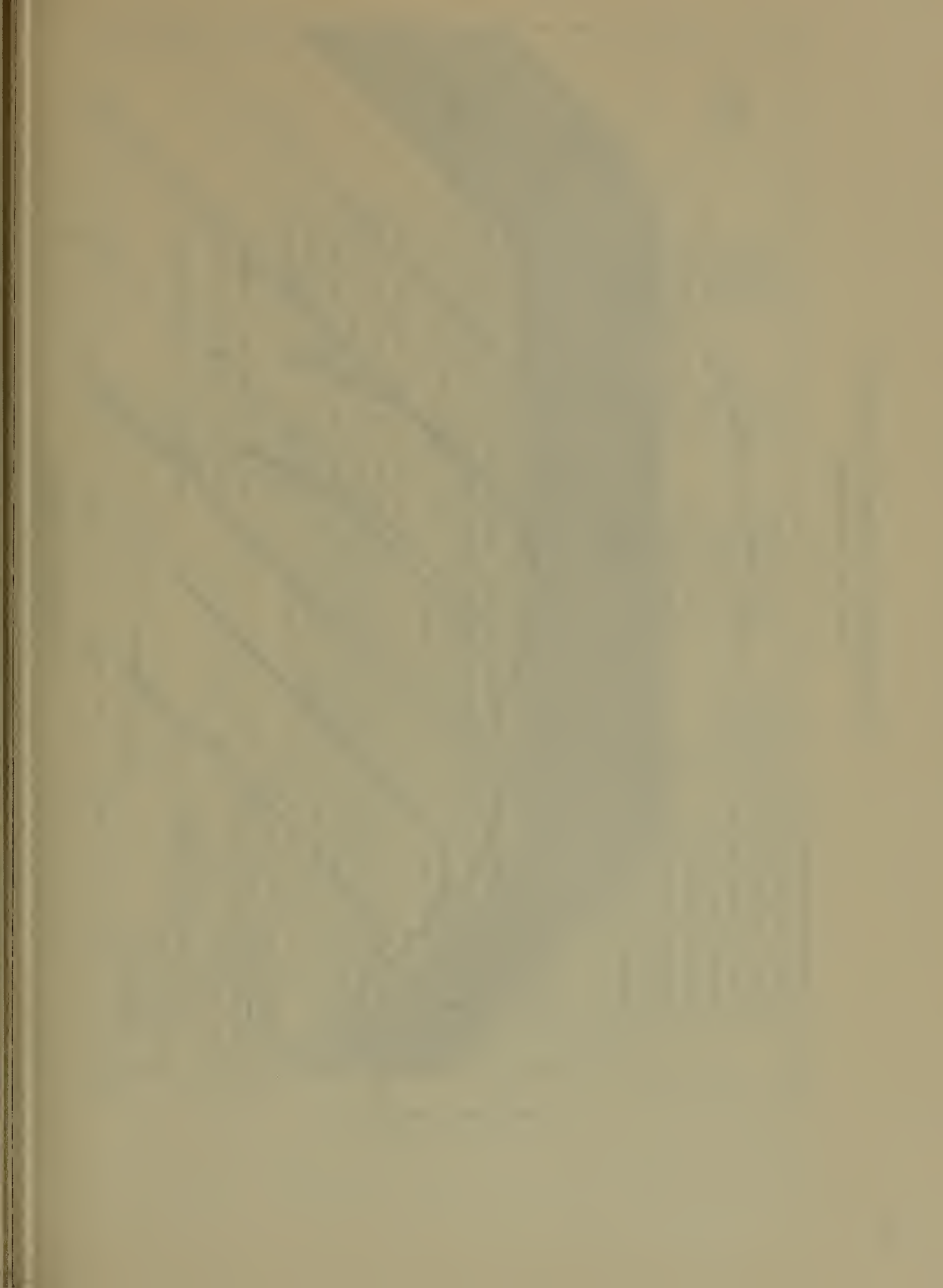
HIGH-FREQUENCY INDUCTANCE (10-1000 MHz)
(LOW-LOSS INDUCTANCE)

66
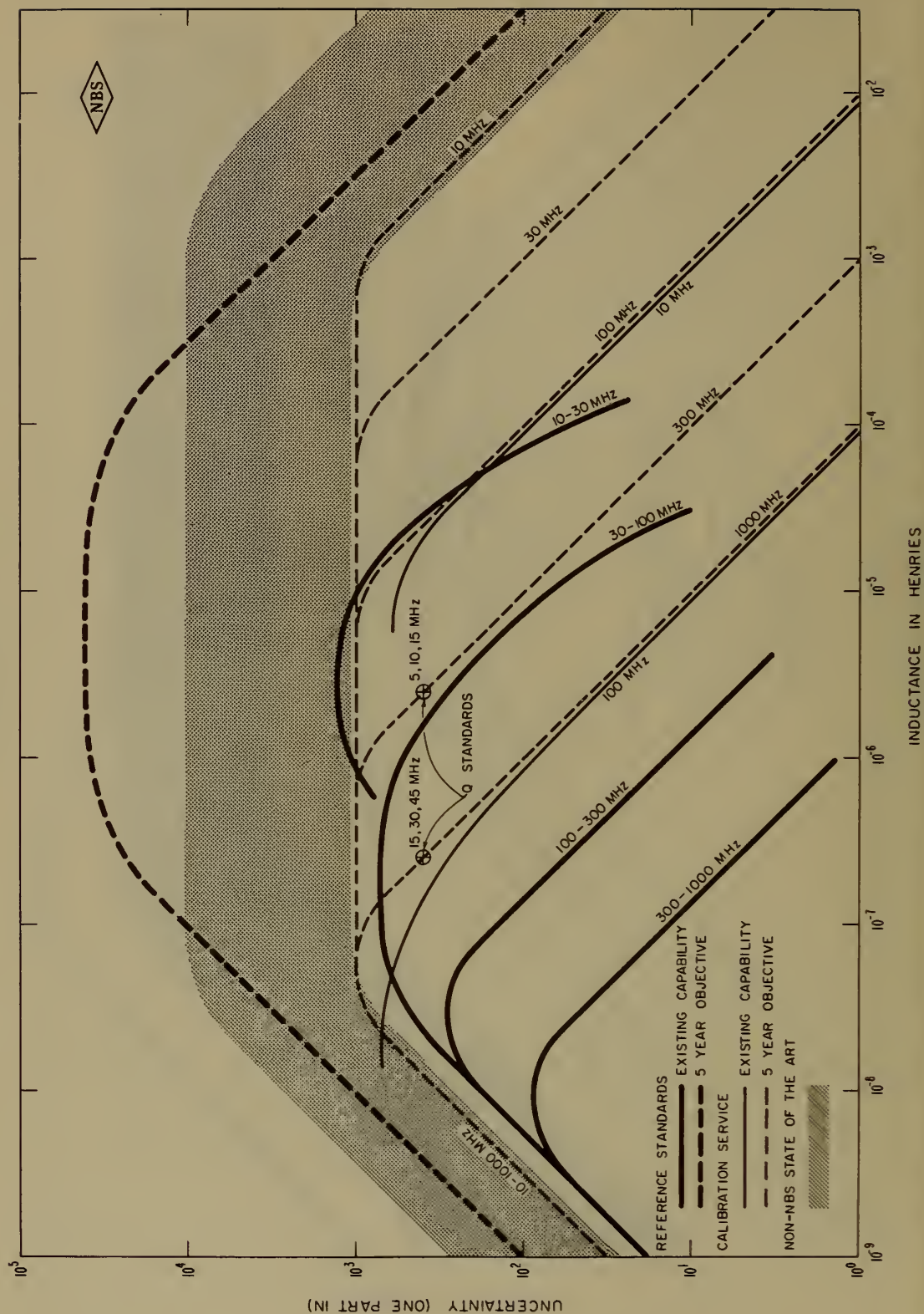
High-Frequency Inductance

C. A. HOER, *Project Leader*, Standards   R. N. JONES, *Project Leader*, Dissemination

Existing capability: The existing calibration service is provided with a Maxwell-type bridge, a Woods-type dual-admittance bridge, resonance techniques, and as negative capacitance on a resistive arm admittance bridge.

The existing reference standards are a slotted line (50 to 500 MHz), a twin-T capacitance bridge (5 to 250 MHz), and a transcomparator (100 kHz to 30 MHz). These reference standards are essentially instruments for comparing an unknown inductor with either the calculated inductance of a length of precision air coaxial line or with the calculated capacitance of a precision variable coaxial capacitor. The general pyramid shape of the accuracy curves is determined by residual resistance or resolution of inductance on the low inductance side and by shunt capacitance on the high inductance side.

State of the art: The shaded band on the chart represents the non-NBS state of the art of low loss inductance measurements at optimum frequencies for specified values. The upper limit of the band represents the precision with which two inductors may be compared, while the lower limit of the band represents the best accuracy with which an inductor may be measured. For clarity, the bands shown are for the lower frequencies only. Typical data used to determine the state of the art follow:

Organization	Uncertainty	Inductance range	Frequency
Commercial standards laboratory	1 part in 6000	10^{-3} H	1 MHz.
Commercial standards laboratory	1 part in 4000	10^{-4} H	3 MHz.
Commercial standards laboratory	1 part in 900	10^{-5} H	10 MHz.
Instrument manufacturer	1 part in 11,000*	$2 \cdot 10^{-5}$ H	100 kHz.
Instrument manufacturer	1 part in 50	10^{-9} H	1000 MHz.
Commercial standards laboratory	1 part in 1000	$5 \cdot 10^{-6}$ H	10 MHz.
Military standards laboratory (England)	1 part in 800	10^{-8} H	250 MHz.
Military standards laboratory (England)	1 part in 1000	10^{-5} H	10 MHz.

*Comparison precision.

HIGH-FREQUENCY ATTENUATION
(COAXIAL SYSTEMS)
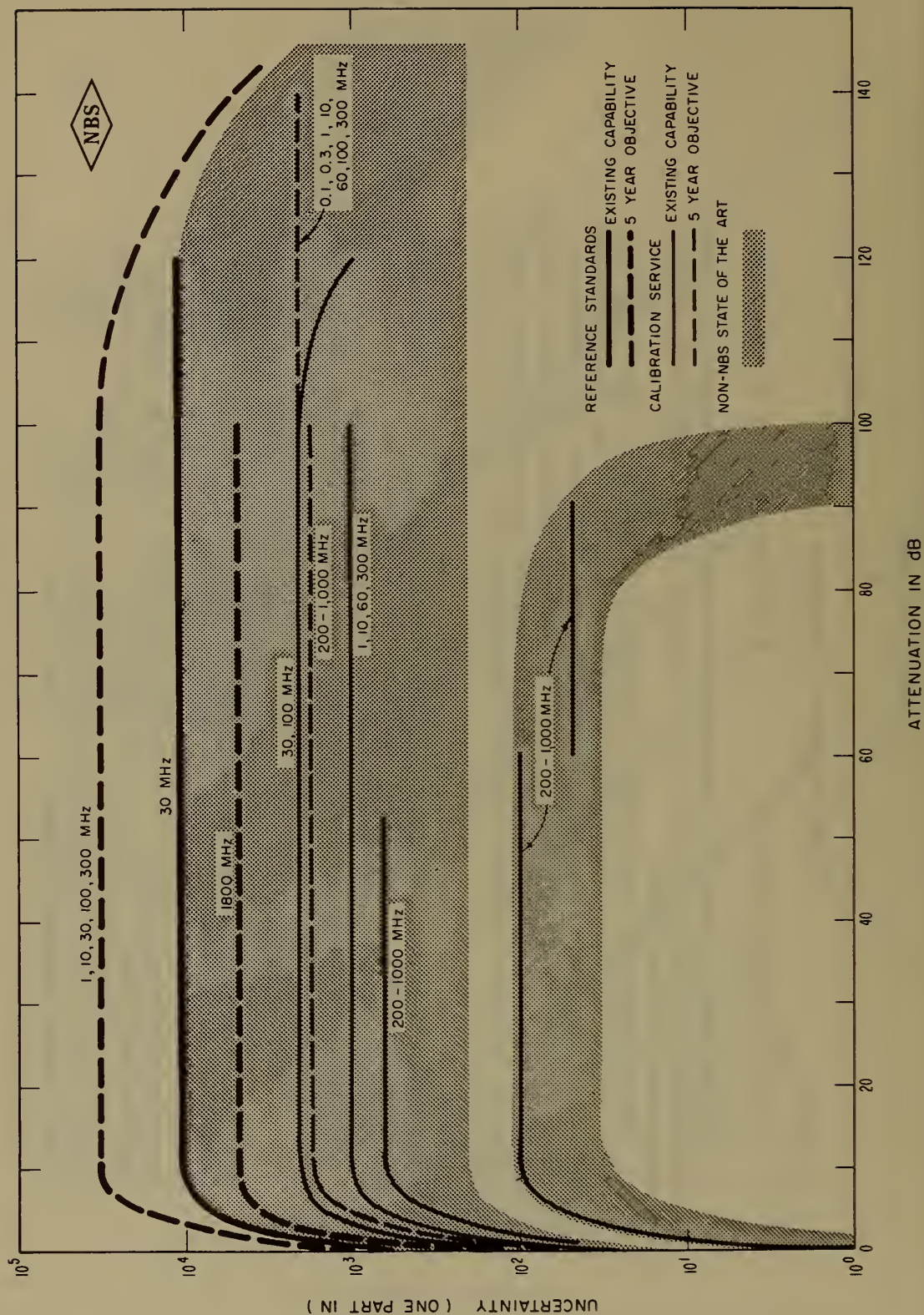
High-Frequency Attenuation

W. R. Ives, *Project Leader,* Standards

D. H. Russell, *Project Leader,* Dissemination

General: The uncertainties are given for both attenuation difference and insertion loss. Attenuation difference applies to variable attenuators. Insertion loss applies to cases where the circuit has to be broken to insert a device. In general, uncertainties cannot be predicted for either method when nonprecision connectors are used.

The uncertainty for small values of attenuation approaches a fixed fraction of a decibel. Thus, as the attenuation to be measured decreases, the uncertainty must increase. For example, if the uncertainty and the measured attenuation were the same, the uncertainty would be 1 part in 1. The dropoff at large values of attenuation is caused by the constantly decreasing signal-to-noise ratio.

The uncertainty is given as a part of the total measured range. For example, 1 part in 10^4 for 80 dB attenuation would give a total uncertainty of 0.008 dB.

The chart represents all errors added in magnitude as the worst possible case. For a general discussion of accuracy and systematic errors, see the reference noted.

Existing capabilities: The frequency range 1 to 300 MHz is based on the use of a waveguide-below-cutoff attenuator at the measuring frequency. Limitations in accuracy are due primarily to uncertainties in producing and measuring small increments of linear displacement, and to uncertainties in the rf conductivity and the diameter of the waveguide. The frequency range 300 to 1000 MHz is based on a heterodyne system and has an additional error and limitation in total measuring range due to mixer nonlinearity.

Five-year objective: Future planning is based primarily on completion of a new 30-MHz reference standard now under development.
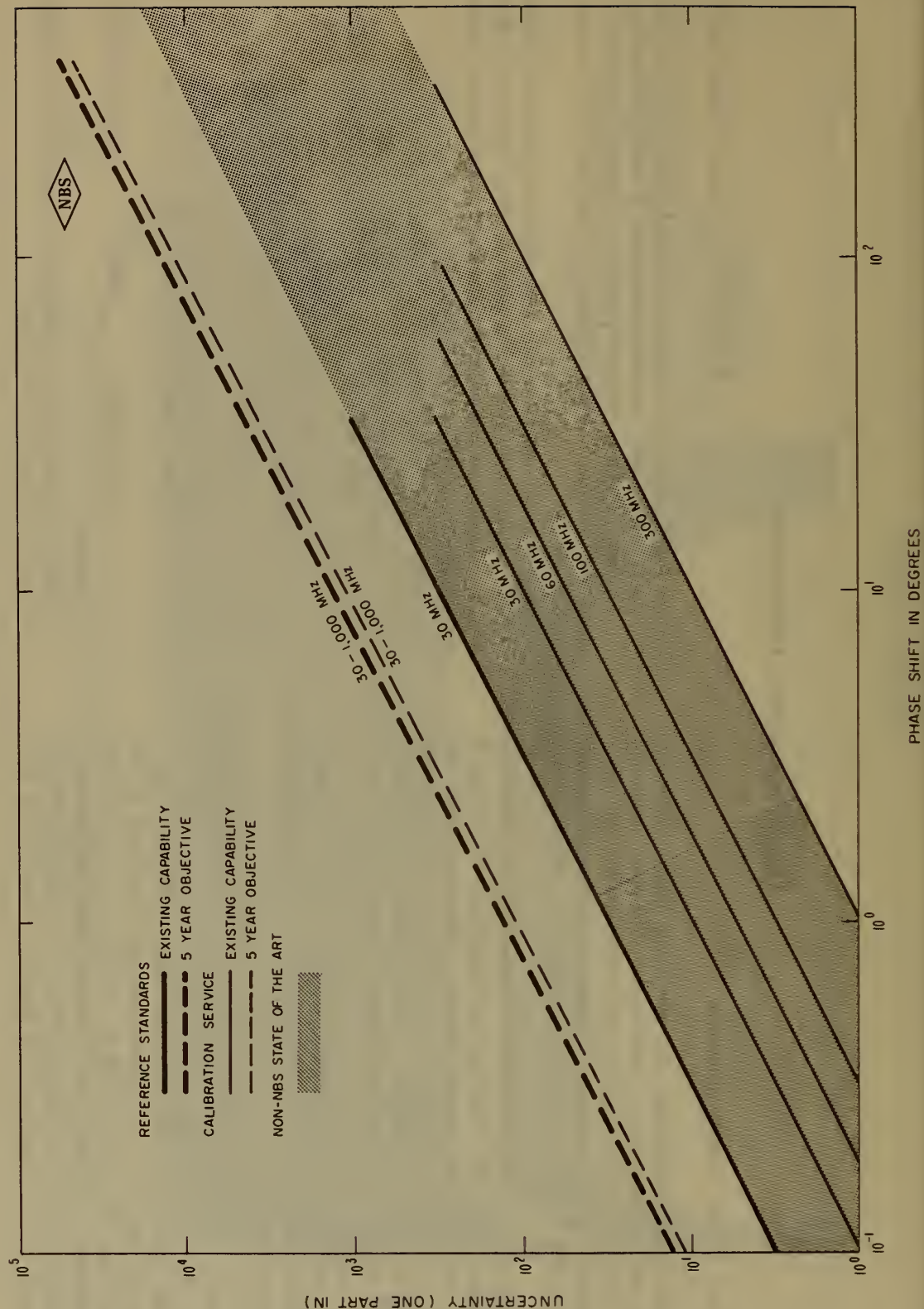
State of the art: Data for the state-of-the-art bands are based on NBS experience in attenuation measurements, information from other standards laboratories, and instrument manufacturers' claims and specifications such as the following:

Manufacturer	Uncertainties	Range	Frequency
I-----------	1 part in 10,000-----	0-60 dB---	30 MHz.
I-----------	1 part in 500-------	0-60 dB---	200-1000 MHz.
II----------	1 part in 1000-----	0-100 dB--	30 MHz.
II----------	1 part in 200------	0-100 dB--	30 MHz.
II----------	1 part in 160------	0-60 dB---	30-1000 MHz.
III---------	1 part in 1000-----	0-100 dB--	30 MHz.
III---------	1 part in 500------	0-100 dB--	30 MHz.
IV----------	1 part in 500------	0-80 dB---	30 and 60 MHz.

Reference:

Altred, C. M., and C. C. Cook, A precision RF attenuation calibration system. IRE Trans. Instr. I-9, No. 2 (Sept. 1960).

HIGH–FREQUENCY PHASE SHIFT
(TWO–PORT COAXIAL DEVICES)

PHASE SHIFT IN DEGREES

UNCERTAINTY (ONE PART IN)

REFERENCE STANDARDS
EXISTING CAPABILITY
5 YEAR OBJECTIVE

CALIBRATION SERVICE
EXISTING CAPABILITY
5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

NBS

30 MHz
60 MHz
100 MHz
300 MHz
30-1,000 MHz
30-1,000 MHz

70

High-Frequency Phase Shift

W. R. Ives, *Project Leader*, Standards   D. H. Russell, *Project Leader*, Dissemination

Existing capability: Phase-shift measurements at fixed frequencies are generally reproducible to within ±0.01 (3 standard deviations). A systematic error in the standard, due to mechanical tolerance limitations, increases the uncertainty to an estimated ±0.1°.

The reference standards are limited in range by mechanical considerations. The reference is a precision "trombone" line stretcher with a mechanical travel of 40 inches. This length corresponds to 36° at 30 MHz, 72° at 60 MHz, etc. Measurement of phase shift at frequencies above 300 MHz is based on a heterodyne measuring system possessing a maximum uncertainty of ±0.1°.

State of the art: Data for the state of the art band were based on NBS experience and manufacturers' published specifications, such as the following:

Manufacturer	Uncertainty	Range	Frequency
I	1 part in 100	0–360°	To 400 MHz.
II	1 part in 20	0–360°	0.1–1000 MHz.
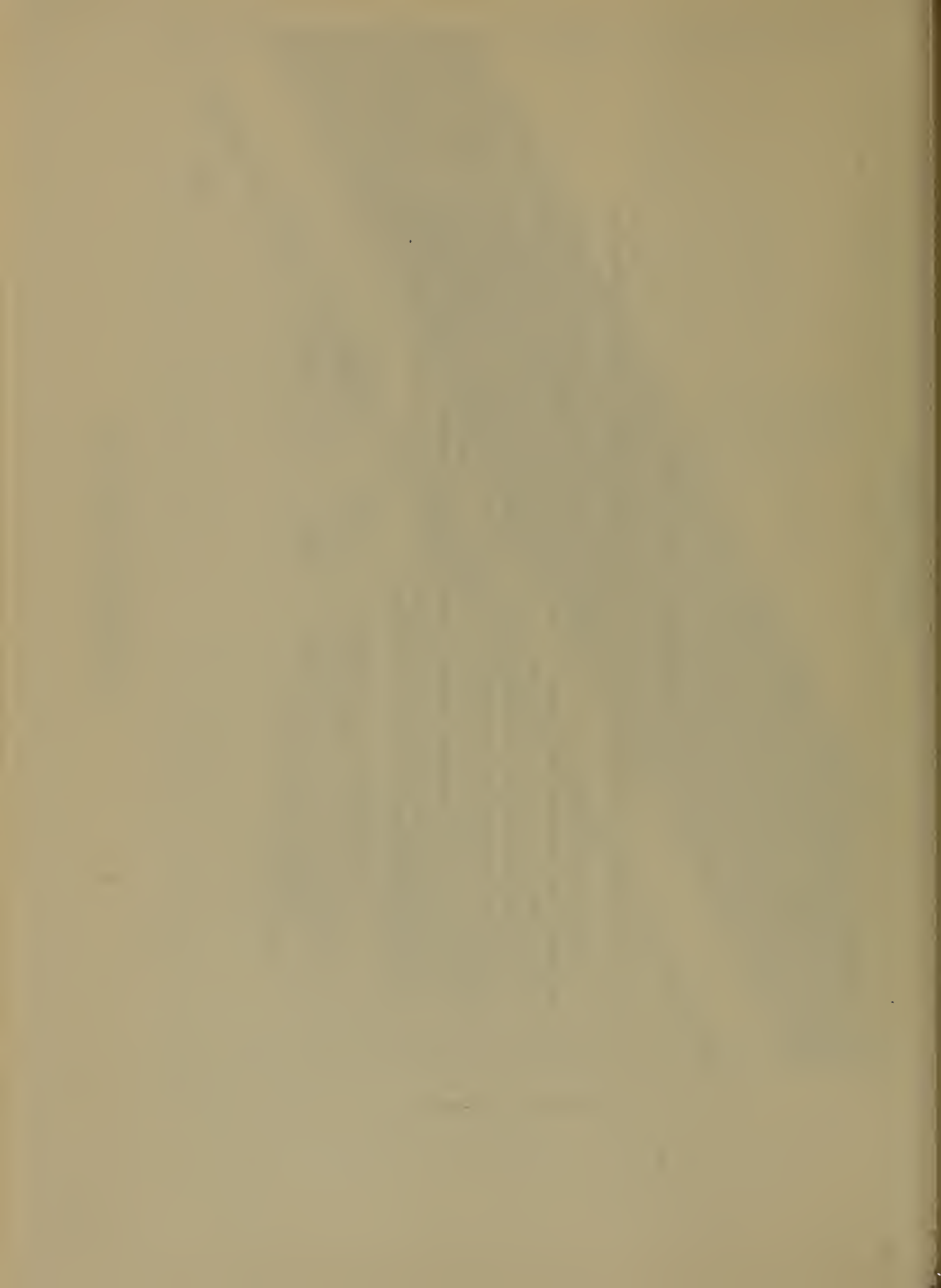
V. Charts for Electrical Quantities, Above 1 GHz

TIME DELAY
(WAVEGUIDE SYSTEMS)

74

Time Delay (Waveguide Systems)

D.A. ELLERBRUCH, *Project Leader*, Standards

General: Time delay, the time for an electromagnetic wave to travel through a device, is given in seconds, but time-delay standards should not be confused with standards of time. The primary reasons for this measurement are twofold:
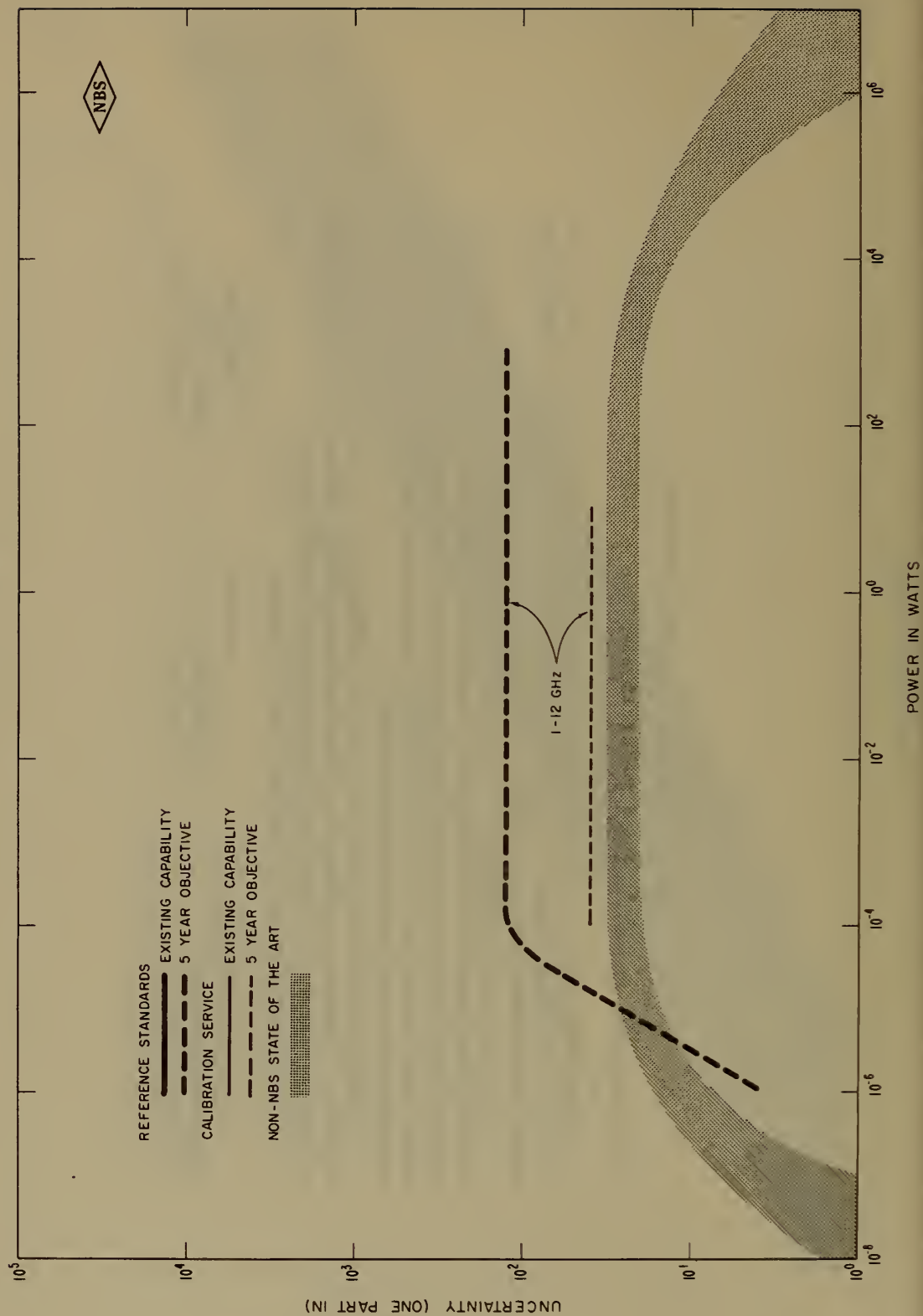
1. It is a measure of phase slope. Any phase slope variation over a frequency band indicates the phase distortion a device or network under test will introduce. Industry has indicated an interest in either phase slope measurements (time delay) or swept-frequency phase data. Where narrow band equipments are involved, time-delay measurement appears to offer the greatest measurement accuracy in the microwave region.

2. Industry has indicated an interest in the measurement of absolute phase through a network or device. Although no technique now exists for determining the absolute phase shift through use of both time delay and phase data, the possibility will be investigated.

State of the art: The band is based partly on the following:

Organization	Uncertainty	Time delay
Commercial laboratory	2×10^{-10} sec.	To 10^{-7} sec.
Instrument manufacturer	2×10^{-9} sec.	To 3.6×10^{-7} sec.

MICROWAVE POWER
(COAXIAL SYSTEMS)

REFERENCE STANDARDS

——— EXISTING CAPABILITY

– – – 5 YEAR OBJECTIVE

CALIBRATION SERVICE

——— EXISTING CAPABILITY

– – – 5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

NBS

1-12 GHz

UNCERTAINTY (ONE PART IN)

POWER IN WATTS

76

Microwave Power (Coaxial Systems)

N. T. LARSEN, *Project Leader*, Low-Power Standards

L. B. ELWELL, *Project Leader*, High-Power Standards

R. F. DESCH, *Project Leader*, Dissemination

Five-year objective: It is planned to fabricate a coaxial reference standard calorimeter covering a frequency range of 1 to 12 GHz from 1 to 100 mW using a single size of coaxial transmission line. Evaluation of the calorimeter will be performed over each frequency band of interest. With this calorimeter, coaxial working standard bolometer units for low power levels can be calibrated. Low-power calibration services can be provided by using these working standards. The power range can be increased by utilizing attenuators and directional couplers.

A coaxial calorimeter for use as a reference standard is planned for this frequency range, covering power levels up to a few hundred watts. This will enable calibrations of bolometer units or thermo-element units in combination with directional couplers or attenuators to be intercompared at power levels above those attainable by low-power bolometric techniques. Calibration services at higher power levels will become available based upon this work.

State of the art: The band representing the non-NBS state of the art illustrates the estimated limits of commercial microwave power-measuring instruments based upon manufacturers' claims. The lower edge of the band corresponds to measurements made at the highest and lowest frequencies; the upper edge corresponds to those made in the middle frequencies.

MICROWAVE POWER
(WAVEGUIDE SYSTEMS)
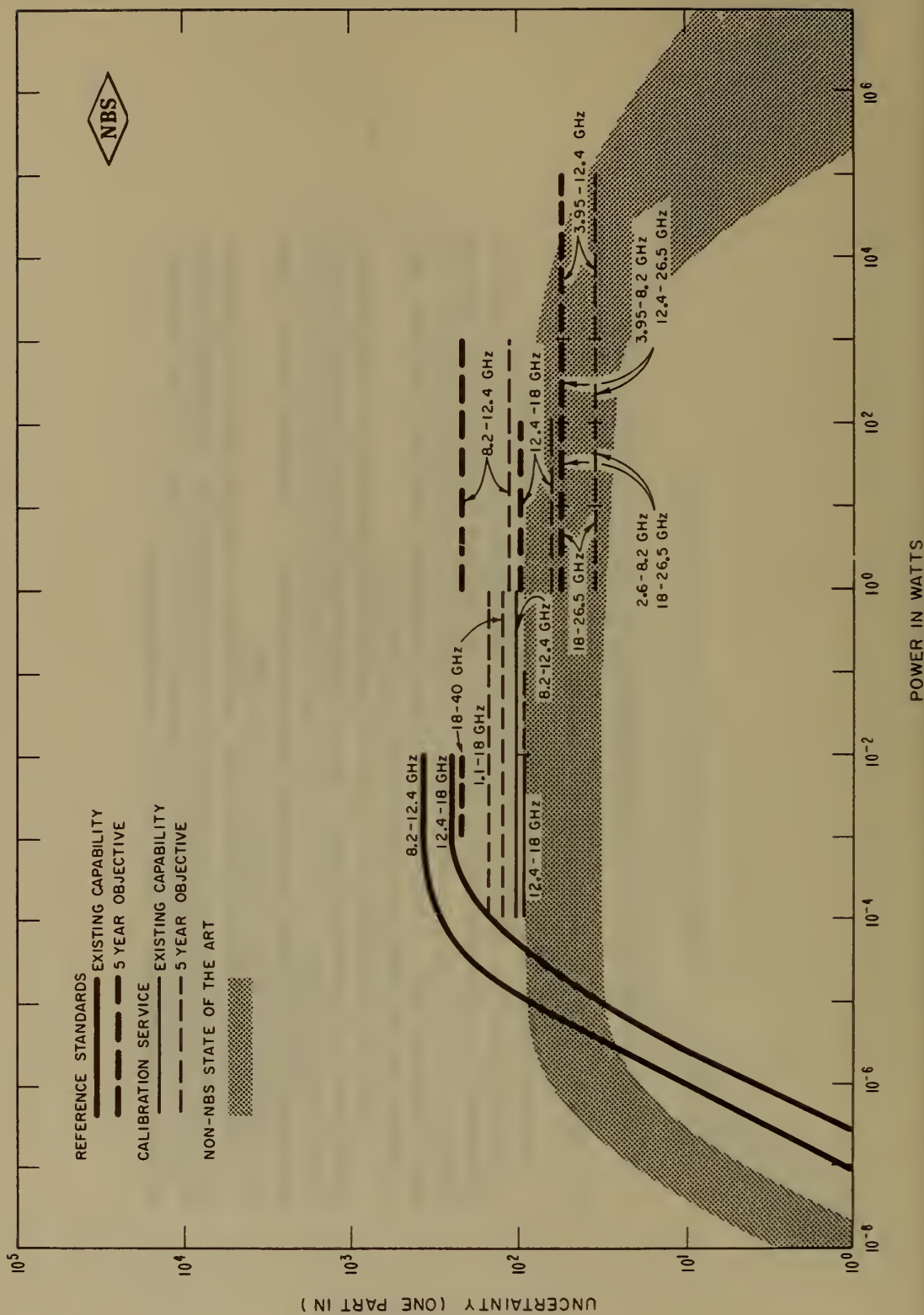
78

Microwave Power (Waveguide Systems)

N. T. LARSEN, *Project Leader*, Low-Power Standards

L. B. ELWELL, *Project Leader*, High-Power Standards

R. F. DESCH, *Project Leader*, Dissemination

General. Calorimetric reference standards used in low-power measurements are not suited for general-purpose power measurement, as they require specially built bolometer mounts. In addition, the labor involved in a single measurement amounts to about 8 man-hours.

The uncertainty is here defined as the limit of error (plus or minus) in the measurement.

Existing capabilities: Reference standards are limited in power range as shown because they are inherently differential devices with a practical range of about 1 to 100 mW. The bolometric technique most generally used is extended by the use of calibrated attenuators. At higher power levels, other techniques are used.

Five-year objective: The projection of standards and calibration services above 1 W is based upon:

(a) A static high-power calorimeter being developed for measurements from 10 to 1000 W.

(b) The use of calibrated low-power meters in combination with calibrated attenuators or directional couplers.

(c) The electron beam microwave power meter technique with an expected range of 10 W to the limitation of the waveguide.

(d) New techniques developed as the result of further study.

Not being a continuous-reading device, the high-power calorimeter is limited in application. With it, the total energy applied in a known time (approximately 3 min) is measured. The two other techniques mentioned have less limited application. We expect an uncertainty of a few percent with the electron beam technique. Its power range is expected to be 10 W to the limits of the waveguide. It should have decreasing value as a standard with increasing frequency, because of limitations presented by the decreasing physical sizes of the waveguides. The frequency range of the standards is, in general, limited by the narrow bandwidth of the waveguide. The design, development, and evaluation of each particular measurement technique must be repeated for each waveguide, size, and type. The calibrations are now performed at spot frequencies in a waveguide band. Applications exist, however, for swept-frequency calibrations.

State of the art: The non-NBS state of the art curve represents an estimate of the limit of the capabilities of modern commercial power-measuring instruments. It is based on manufacturers' claims. The lower edge of the band corresponds to measurements made at the highest and lowest frequencies. The upper edge corresponds to the middle frequencies.

PULSE POWER
(WAVEGUIDE SYSTEMS)

80
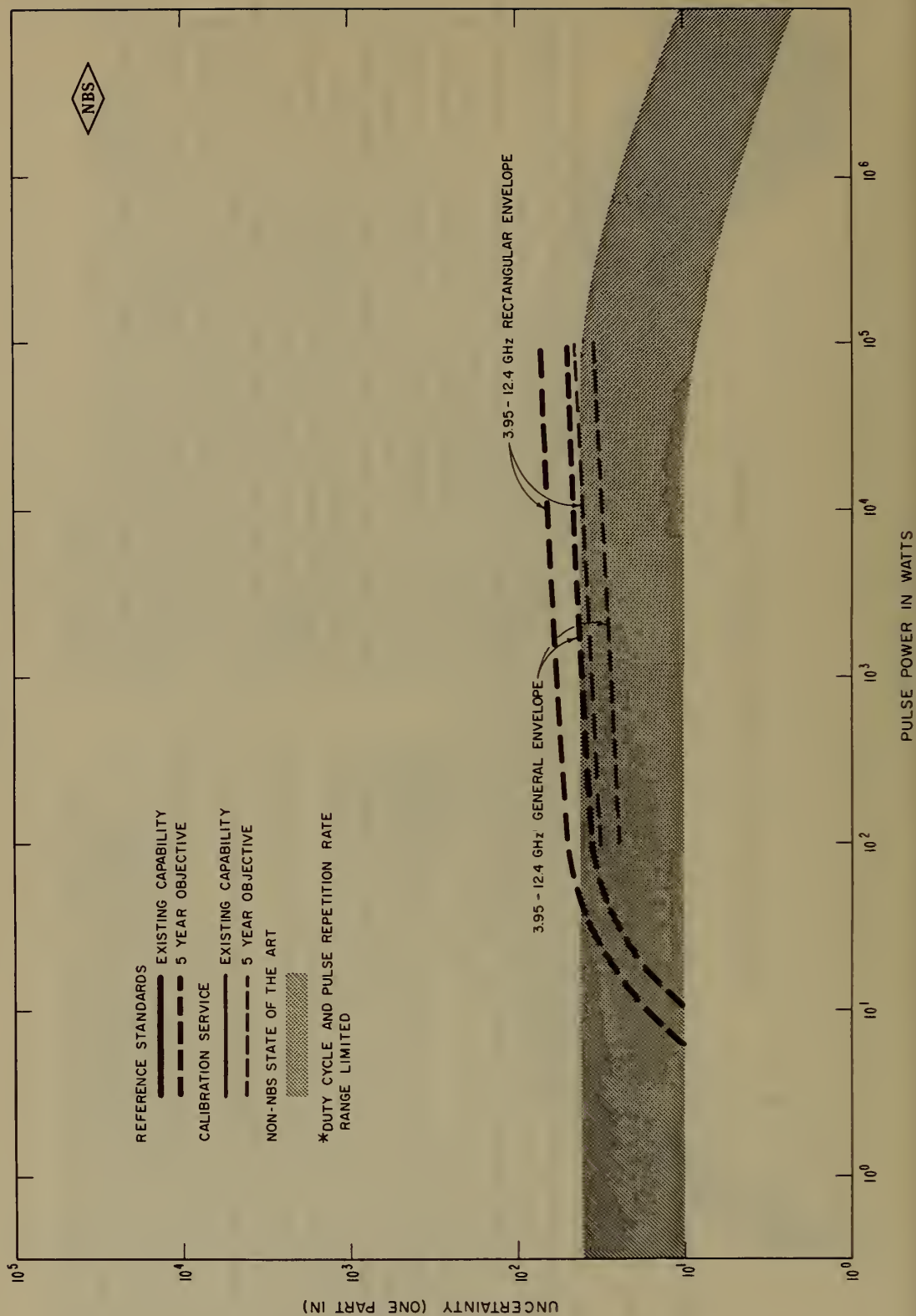
Pulse Power (Waveguide Systems)

N. T. LARSEN, *Project Leader*, Low-Power Standards

R. F. DESCH, *Project Leader*, Dissemination

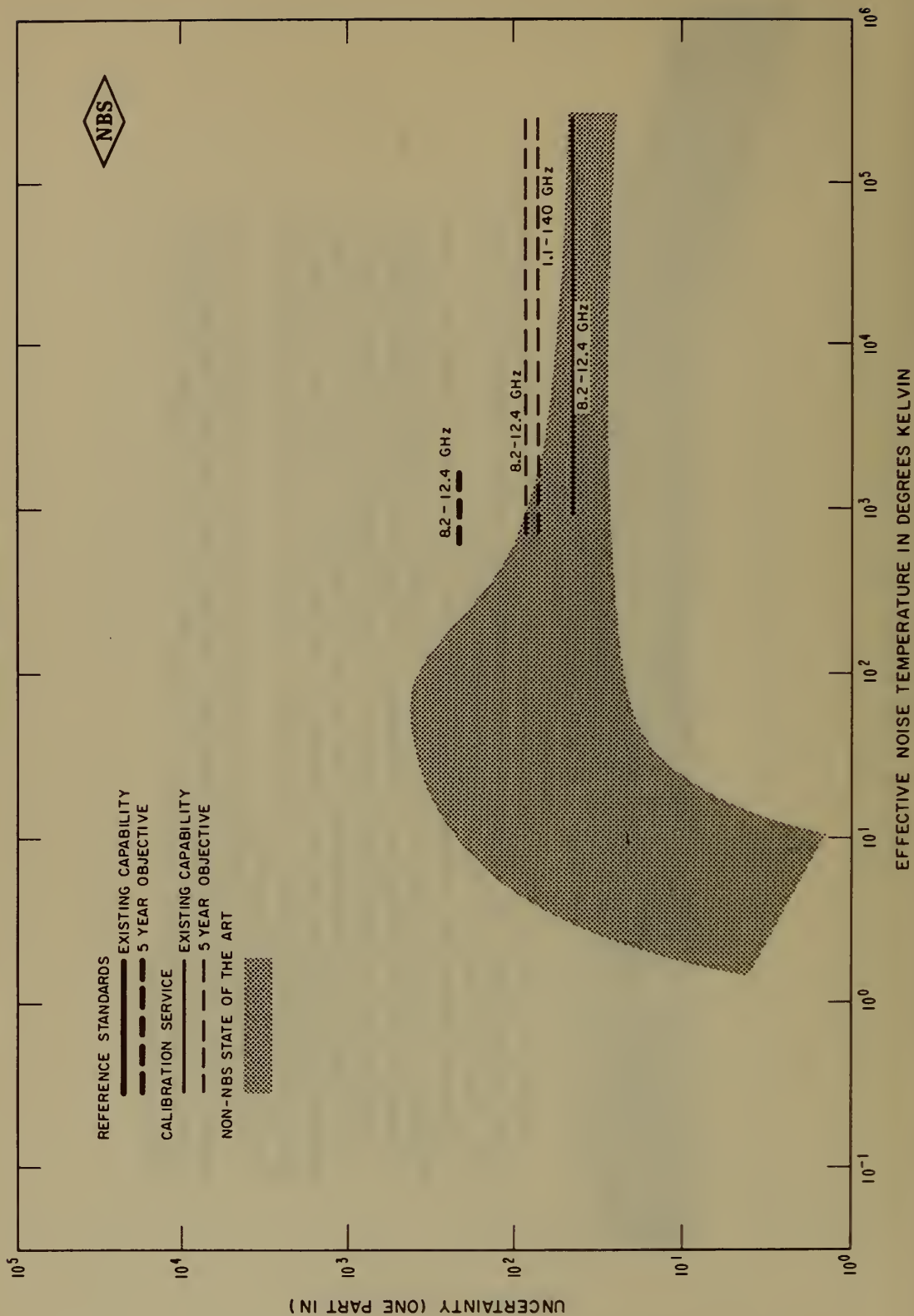L. B. ELWELL, *Project Leader*, High-Power Standards

General: The design, development, and evaluation of a standard must, in general, be repeated for each waveguide size. The effects upon a measurement due to different repetition rates, duty cycles, modulation waveforms, and power levels must be considered.

Five-year objective: The projected standardization of the measurement of peak pulse power in rectangular waveguides is based on completing the development of the electron-beam technique. Decreased uncertainty at higher power levels shown on the chart is characteristic of this technique.

The chart also represents further investigation of existing techniques—for example, measurement by comparing a demodulated waveform with an average power measurement. At present, a technique in coaxial lines has been developed for use below 1 GHz. The peak pulse power is measured by sampling the pulse for a short interval. This sample is compared to a similar sample from a known CW power source.

State of the art: The non-NBS state of the art band is an estimate of the capabilities of commercial equipment and of microwave laboratories. The lower limit of the band represents uncertainties of available commercial equipment. The upper limit represents the possible capabilities of microwave laboratories.

81

MICROWAVE NOISE
(WAVEGUIDE SYSTEMS)

REFERENCE STANDARDS
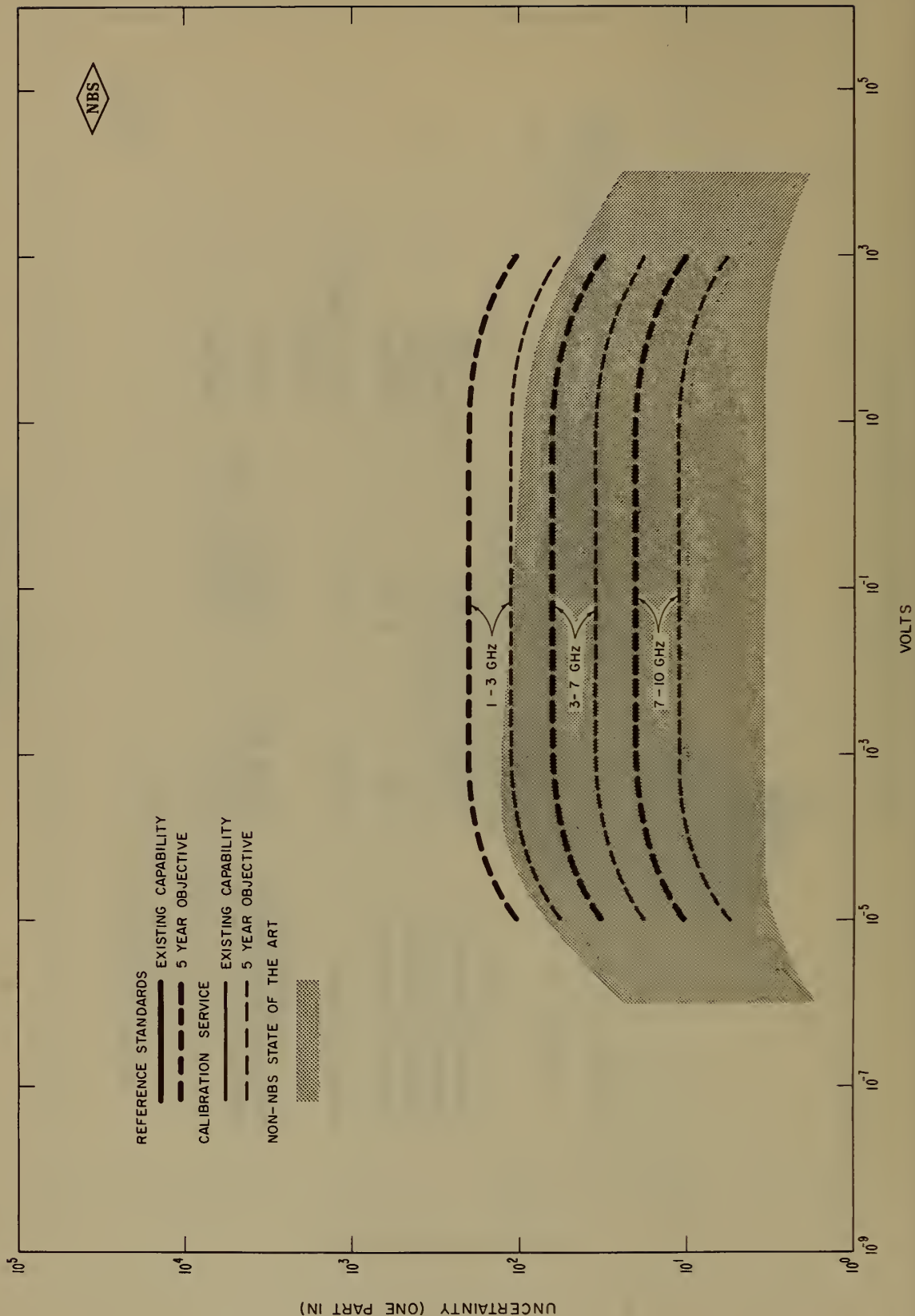━━━━━ EXISTING CAPABILITY
━ ━ ━ 5 YEAR OBJECTIVE

CALIBRATION SERVICE
──── EXISTING CAPABILITY
─ ─ ─ 5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

NBS

8.2 - 12.4 GHz

8.2 - 12.4 GHz

1.1 - 140 GHz

8.2 - 12.4 GHz

EFFECTIVE NOISE TEMPERATURE IN DEGREES KELVIN

UNCERTAINTY (ONE PART IN)

82

Microwave Noise (Waveguide Systems)

G. F. ENGEN, *Project Leader*, Standards   C. K. S. MILLER, *Project Leader*, Dissemination

State of the art: The band is based in part on the following:

Organization	Uncertainty	Effective noise temperature	Frequency
Commercial laboratory	0.5 °K	3.5 °K	4.17 GHz.
Commercial laboratory	0.2 °K	2.3 °K	2.39 GHz.
Commercial laboratory	1 °K	21 °K	2.39 GHz.
Commercial laboratory	1 °K	8 °K	2.39 GHz.
Aerospace industry	0.2 °K	77.5 °K	0.96, 1.3, 2.295, and 9.25 GHz.
USSR standards laboratory	250 °K (2σ)	10,000 °K	1–10 GHz.
USSR standards laboratory	10 °K (2σ)	600–700 °K or 900–1000 °K	1–10 GHz.

MICROWAVE VOLTAGE (C W)

Microwave Voltage (CW)

M. C. SELBY, *Project Leader*, Standards   F. X. RIES, *Project Leader*, Dissemination

Existing capability: No standards presently exist at NBS for CW voltage above 1 GHz.

State of the art: The non-NBS state of the art band is based on claims of other laboratories and claims and specifications of commercial instruments. The upper and lower limits of this band represent uncertainties at frequencies ranging from 1 GHz to 15 GHz respectively. Typical data on which the band is based follow:

Organization	Uncertainty	Voltage range	Frequency
Instrument manufacturer	1 part in 60	0.2–1 V	1 GHz.
Electronic manufacturer	1 part in 10	0.5 mV–1 V	3.5 GHz.
Commercial laboratory	1 part in 5	0.2–3 V	2 GHz.
Research laboratory	1 part in 40	0.05–10 V	3–10 GHz.
Instrument manufacturer	1 part in 5	0.1 mV–25 V	2–10 GHz.

MICROWAVE FIELD STRENGTH
(HORN GAIN)

REFERENCE STANDARDS
  EXISTING CAPABILITY
  5 YEAR OBJECTIVE

CALIBRATION SERVICE
  EXISTING CAPABILITY
  5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

UNCERTAINTY (ONE PART IN)

FREQUENCY IN Hz

86
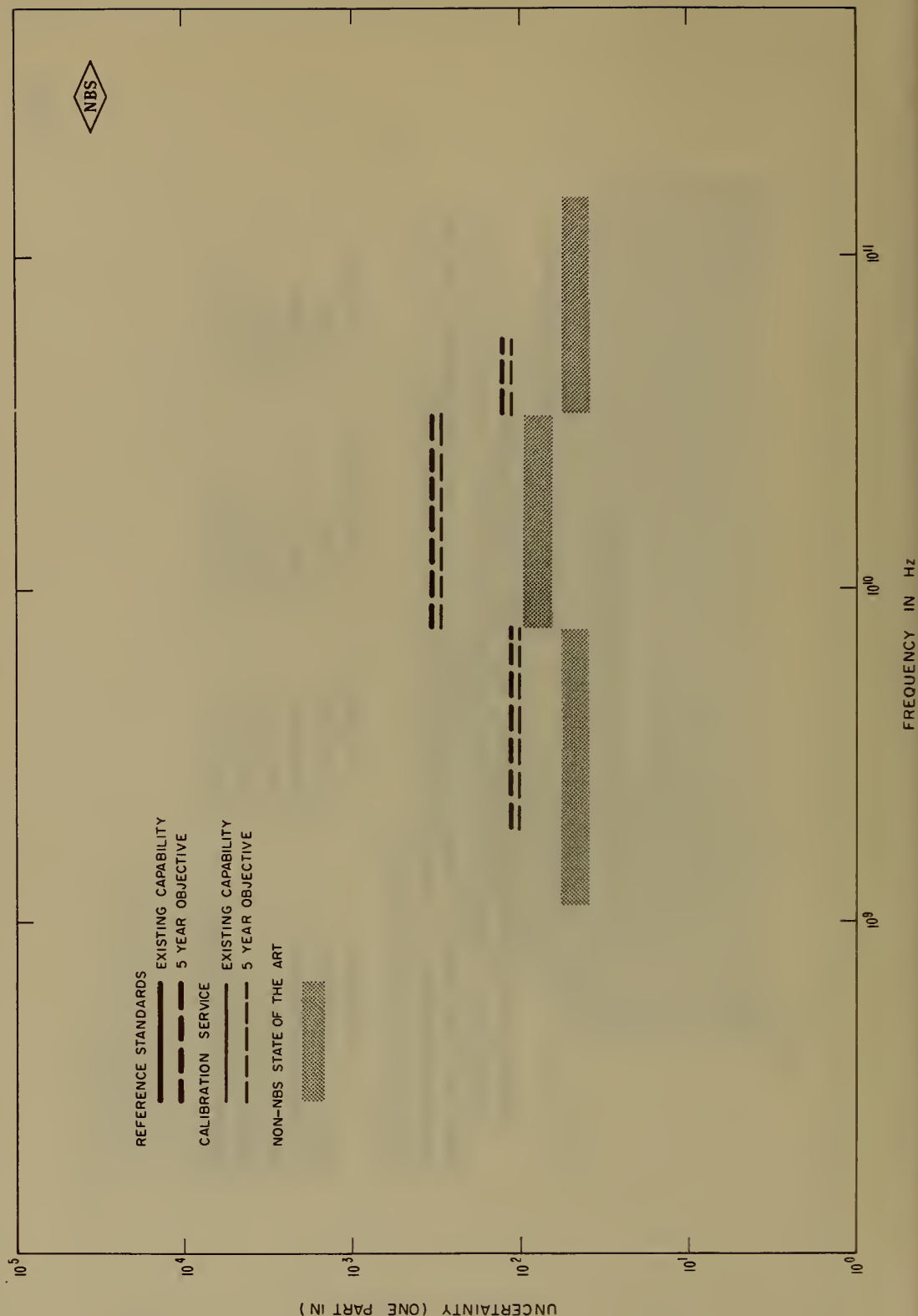
Microwave Field Strength (Horn Gain)

R. R. BOWMAN, *Project Leader*, Standards

General: The uncertainty of horn gain calibrations depends on waveguide size. At long wavelengths the calibration uncertainty is imposed by the dimensions of the anechoic chamber, while at sufficiently short wavelengths the uncertainty is imposed by the small waveguide dimensions. A more detailed graph, therefore, would show a different uncertainty for each frequency band. Since the variations are not great over the indicated range of frequencies, only three levels suggesting the limits of the uncertainties are shown.

Five-year objectives: Achievement of the objectives is contingent on the availability of a finished anechoic chamber by the end of Fiscal Year 1965.

State of the art: Standard gain horns provided by industry are usually not calibrated experimentally. These horns are constructed to dimensions specified in Naval Research Laboratory Report No. 4433. The limits of error established by NRL Report 4433 are ± 0.3 dB, or about 7 percent.

MICROWAVE ATTENUATION
(COAXIAL SYSTEMS)

88
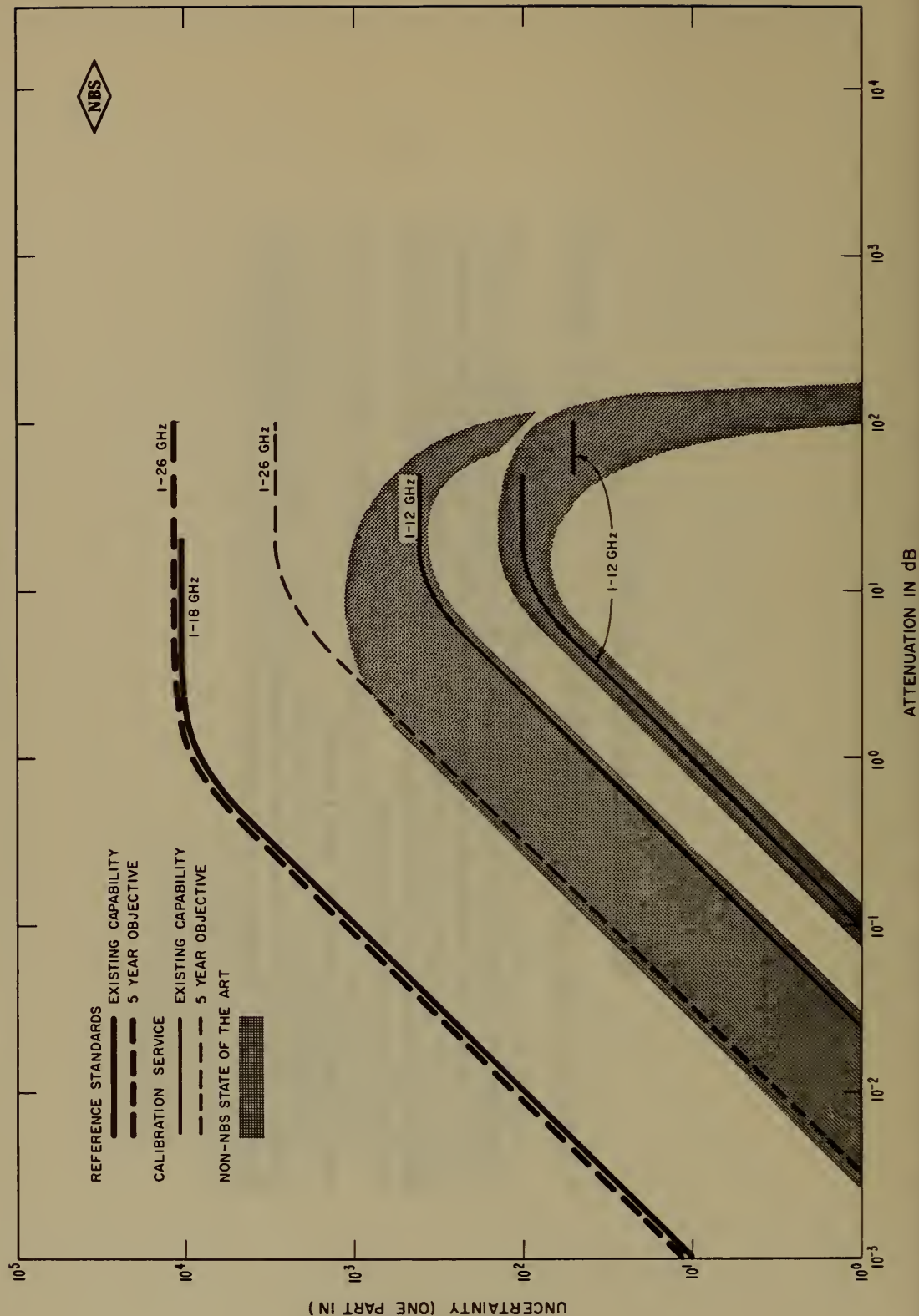
Microwave Attenuation (Coaxial Systems)

D. A. ELLERBRUCH, *Project Leader*, Standards   D. H. RUSSELL, *Project Leader*, Dissemination

Existing capability: The power-ratio method is used from 0 to 50 dB and either the IF substitution or modulated subcarrier method is used for the higher attenuations.

A 30-MHz waveguide-below-cutoff attenuator in conjunction with a diode mixer is considered the reference standard of attenuation.

Five-year objective: The five-year objective for the 1 to 26 GHz frequency range extends the range to 100 dB with decreased uncertainty. A portion of the decreased uncertainty will be due to the use of improved impedance-matching techniques reducing mismatch error.

State of the art: The lower shaded area, representing the non-NBS state of the art for insertion loss measurement, includes uncertainties due to mismatch error. The upper non-NBS state of the art band represents attenuation difference measurements in which mismatch error is not included. Typical data used in determining the state of the art follow:

Organization	Uncertainty	Attenuation	Frequency
Instrument manufacturer	1 part in 500	0–60 dB	1–10 GHz.
Instrument manufacturer	1 part in 160	60–100 dB	1–10 GHz.
Instrument manufacturer	1 part in 160	0–100 dB	1–11 GHz.
Aerospace company	1 part in 160	0–100 dB	1–11 GHz.
Aerospace company	1 part in 160	0.5 dB	2–12 GHz.
Aerospace company	1 part in 1000	30 dB	2–12 GHz.

MICROWAVE ATTENUATION
(WAVEGUIDE SYSTEMS)

◇NBS◇

REFERENCE STANDARDS
—— EXISTING CAPABILITY
--- 5 YEAR OBJECTIVE

CALIBRATION SERVICE
—— EXISTING CAPABILITY
--- 5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

1-40 GHz
8.2-12.4 GHz
40-220 GHz
1-40 GHz

2.6-12.4 GHz
8.2-26.5 GHz
1-17.2.6-12.4 GHz
5.8-8.2.2.6-12.4 GHz
1-11.7
1-40 GHz
40-140 GHz
12.4-40 GHz

ATTENUATION IN dB

UNCERTAINTY (ONE PART IN)

90
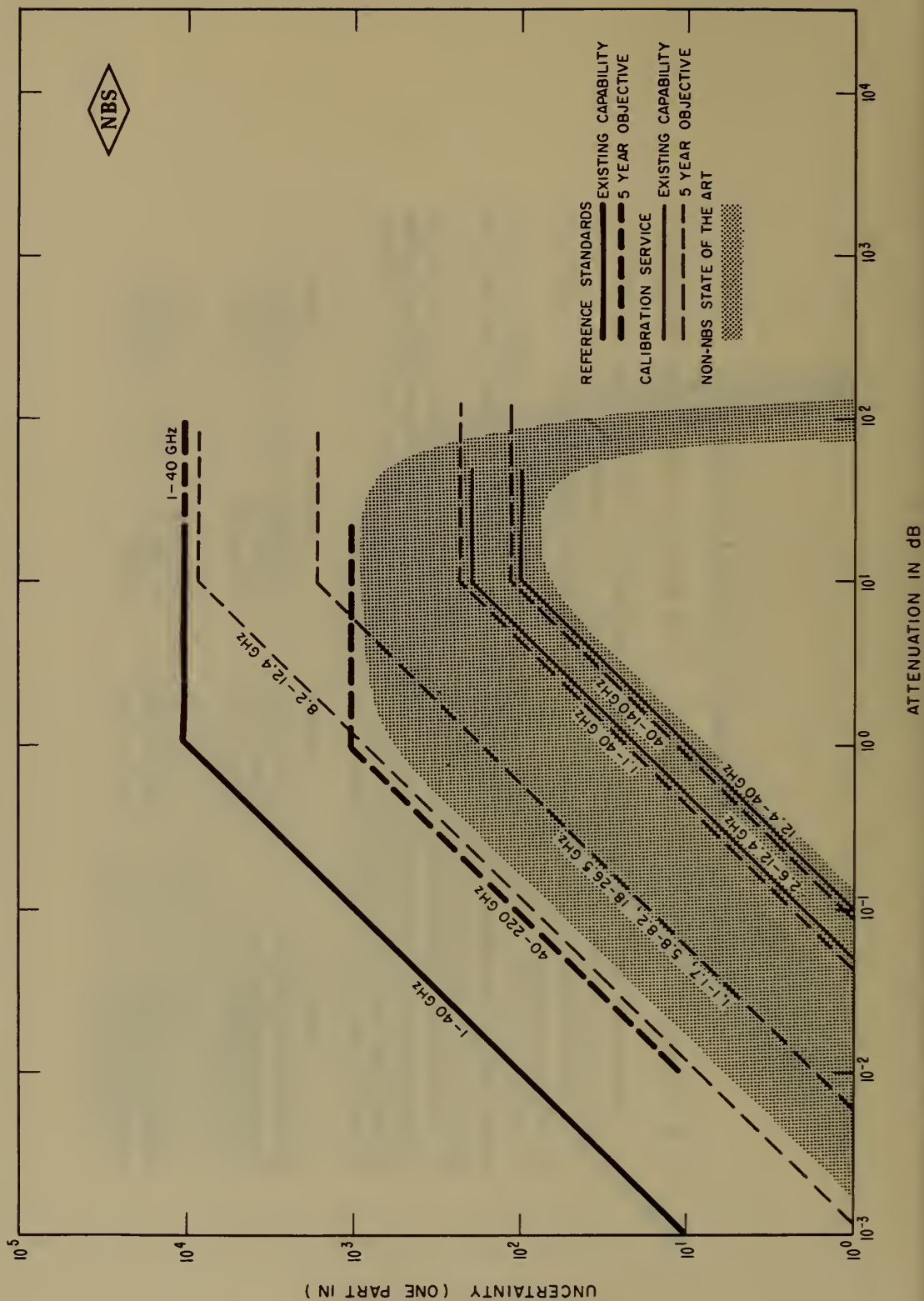
Microwave Attenuation (Waveguide Systems)

D. A. ELLERBRUCH, *Project Leader*, Standards   W. LARSON, *Project Leader*, Dissemination

General: Mismatch error is the most important limiting factor in the existing capability curve. Highly refined matching techniques must be used to achieve the accuracy represented by the present curve.

Existing capability: The existing capability curve for reference standards represents two different measurement techniques: the power-ratio method from 10^{-3} to 10^{0} dB, and the modulated subcarrier method for the rest of the curve.

Five-year objective: The five-year objective for the frequency range of 1 to 40 GHz is an extension of the modulated subcarrier method to a range of 100 dB.

The five-year objective for the 40 to 220 GHz range is the development of systems using the 30-MHz IF substitution technique of attenuation measurement. The curve falls far below the existing capability curve because of the many uncertainties, such as source stability and mixer crystal properties, that have not been determined.

State of the art: The non-NBS state of the art band represents the estimated uncertainty of commercial instruments. The frequency range covered by the band extends from about 1 GHz at the upper limit to 40 GHz at the lower limit. Typical data from which the state of the art was determined follow:

Organization	Uncertainty	Attenuation
Instrument manufacturer	1 part in 600	120 dB.
Instrument manufacturer	1 part in 50	50 dB.
Aerospace industry	1 part in 170	0.5 dB.
Aerospace industry	1 part in 1000	30 dB.

MICROWAVE PHASE SHIFT
(TWO-PORT WAVEGUIDE AND COAXIAL DEVICES)

PHASE SHIFT IN DEGREES

UNCERTAINTY (ONE PART IN)

REFERENCE STANDARDS
EXISTING CAPABILITY
5 YEAR OBJECTIVE

CALIBRATION SERVICE
EXISTING CAPABILITY
5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

1.1 - 40 GHz
8.2 - 12.4 GHz
40 - 90 GHz (WAVEGUIDE ONLY)
1.1 - 40 GHz

92
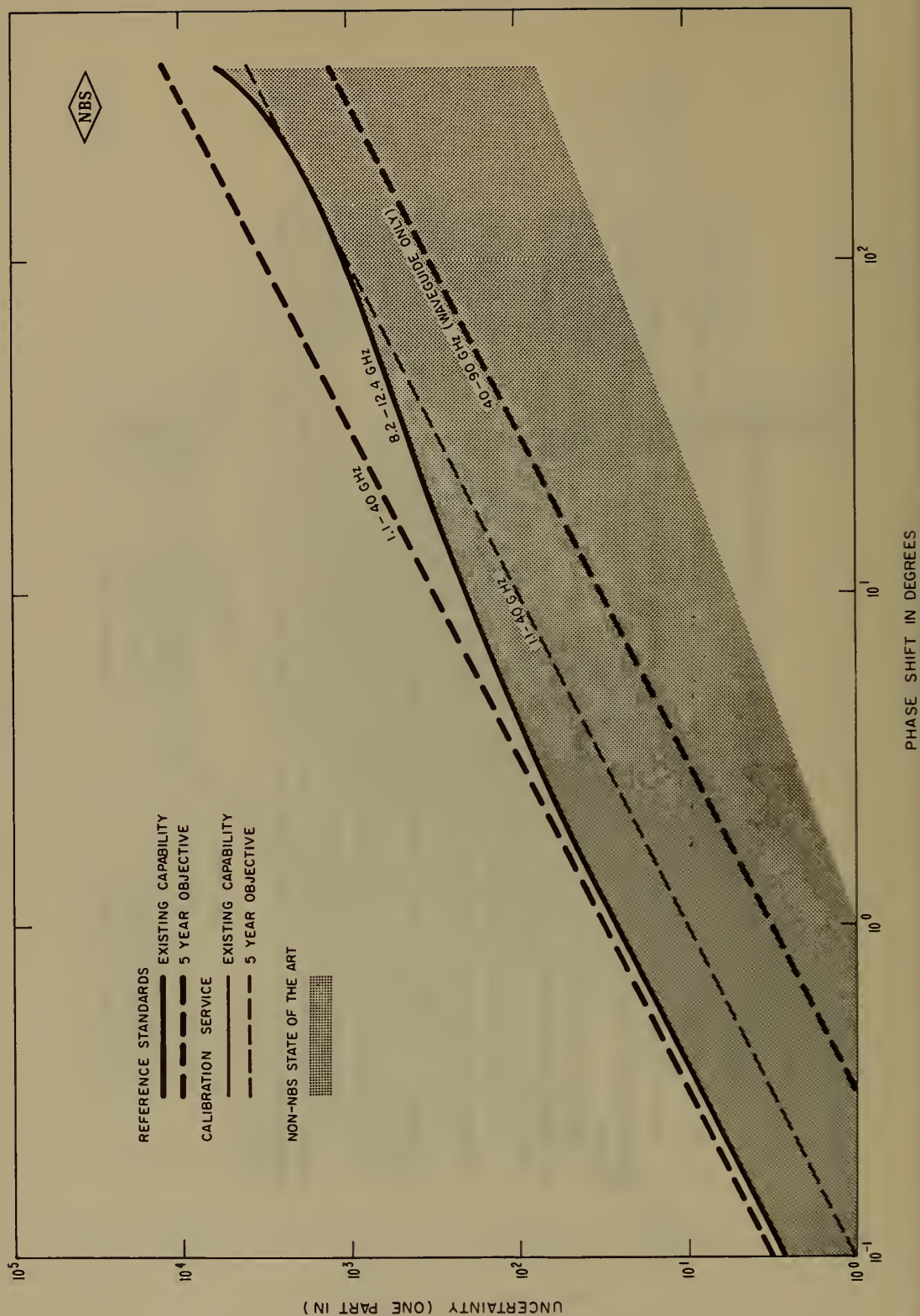
Microwave Phase Shift (Two-Port Waveguide and Coaxial Devices)

D. A. ELLERBRUCH, *Project Leader*, Standards

D. H. RUSSELL, *Project Leader*, Dissemination, Coaxial

W. LARSON, *Project Leader*, Dissemination, Waveguide

General: The uncertainty is determined by summing the individual limits of errors from all sources. This total limit of error is now determined by precision waveguide tolerances, short-circuit displacement measurements, and matching.

Existing capability: NBS does not yet offer phase-shift calibration services. The measurement capability for X-band waveguide devices is shown on the graph along with the range of the state of the art for industry.

The X-band reference standard accuracy curves are derived for a modified reflectometer terminated in a sliding short circuit as the standard.

State of the art: The non-NBS state of the art band shown is drawn from personal knowledge and studies of various commercial techniques. Typical data used follow:

Organization	Uncertainty	Phase shift
Aerospace company	1.5°	To 360°.
Instrument manufacturers	1°+1 percent	To 360°.
Aerospace company	0.3°	To 360°.

MICROWAVE REFLECTION COEFFICIENT
(COAXIAL SYSTEMS)

MAGNITUDE OF REFLECTION COEFFICIENT

UNCERTAINTY (ONE PART IN)

REFERENCE STANDARDS
——— EXISTING CAPABILITY
━━━ 5 YEAR OBJECTIVE

CALIBRATION SERVICE
——— EXISTING CAPABILITY
- - - - 5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

1-12.4 GHz.

1-12.4 GHz

1-8 GHz
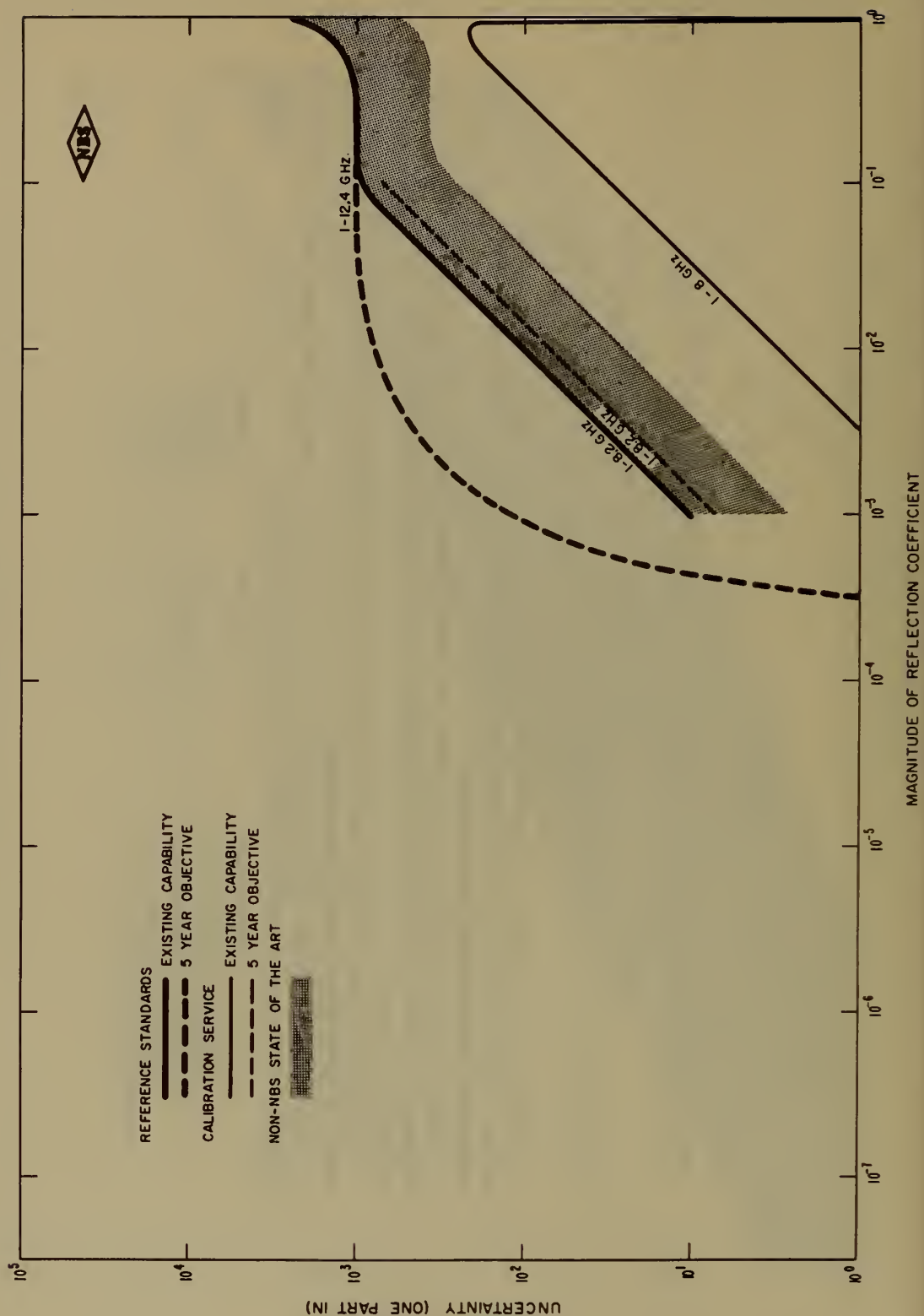
Microwave Reflection Coefficient (Coaxial Systems)

W. E. LITTLE, *Project Leader*, Standards   R. N. JONES, *Project Leader*, Dissemination

General: The curves are based on reflectometer measurement techniques, using quarter-wave-length short circuits as reference standards.

Existing capability: At present, waveguide-to-coaxial couplers are used on rectangular wave-guide systems.

Five-year objective: The future systems are planned to be completely coaxial.

State of the art: The non-NBS state-of-the-art band is based on both reflectometer and improved slotted-line techniques, but is limited to devices equipped with high-precision coaxial connectors.

References:

F. R. Huber and H. Neubauer, Measurement techniques for the determination of the major characteristics of coaxial components, *Microwave J.* 5, 196–203 (*Sept. 1962*).

A. E. Sanderson, A new high precision method of measurement of the VSWR of coaxial connectors, *IRE Trans. Microwave Theory Tech.* MTT–11, *No. 7, 524–528 (Nov. 1961).*

B. O. Weinschel, Air filled coax lines as absolute impedance standards, *Microwave J.* 7, *No. 4, 47–50 (Apr. 1964).*

D. Woods, A coaxial connector system for precision RF measuring instruments and standards, *Proc. IEE 108, Pt. B, No. 38, 205–213 (1961).*

Improved sweep frequency techniques for broadband microwave testing, *Hewlett-Packard J.* 12, *No. 4 (Dec. 1960).*

Time domain refletometry. *Hewlett-Packard J.* 15, *No. 6 (Feb. 1964).*

MICROWAVE REFLECTION COEFFICIENT (WAVEGUIDE SYSTEMS)
(MAGNITUDE OF REFLECTION COEFFICIENT)

REFERENCE STANDARDS
　　EXISTING CAPABILITY
　　5 YEAR OBJECTIVE
CALIBRATION SERVICE
　　EXISTING CAPABILITY
　　5 YEAR OBJECTIVE
NON-NBS STATE OF THE ART

2.6 - 12.4 GHz

60 - 90 GHz

1.1 - 90 GHz

8.2 - 18 GHz

1.1 - 90 GHz

UNCERTAINTY (ONE PART IN)

REFLECTION COEFFICIENT MAGNITUDE

NBS

96
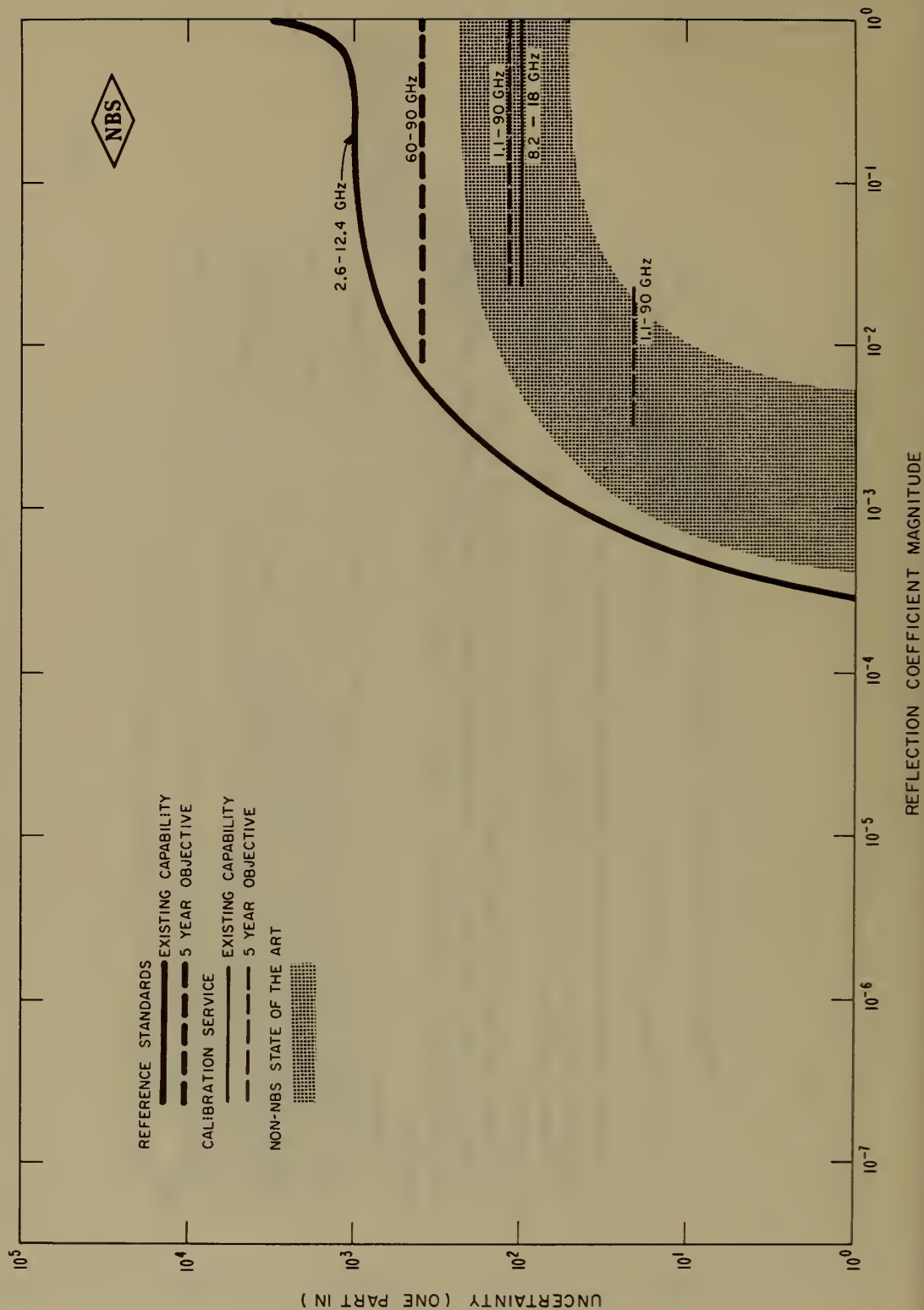
Microwave Reflection Coefficient (Waveguide Systems)

W. E. Little, *Project Leader*, Standards   B. C. Yates, *Project Leader*, Dissemination

General: The curves are based on reflectometer measurement techniques, using quarter-wave-length short circuits as the reference standards.

Five-year objective: The five-year objective for the 60 to 90 GHz frequency range is to develop a reflectometer and suitable reference standards in rectangular waveguide.

Improvements over the existing capability curve for the 2.6 to 12.4 GHz frequency range are limited by the mechanical precision to which a waveguide can be manufactured and by the stability and accuracy of small power or voltage ratio measurements.

State of the art: The non-NBS state of the art band represents capabilities in the frequency region below 12.4 GHz only.

References:

H. M. Altschuler, Measurement of arbitrary linear microwave two ports, *Proc. IEE 109, Pt. B, Suppl. 23, 704–712* (1962).

J. K. Chamberlain and B. Easter, Direct reading waveguide impedance and reflection indicator, *Electronic Eng.* **34,** *No. 407, 14–20 (Jan. 1962).*

C. S. Gledhill and B. P. Walker, Microwave bridge reflectometer, *Proc. IEE 110, 1759 (Oct. 1963).*

R. J. Wescott, Equipment for display of reflection coefficient over a 50 Mc band at 35 Gc, *Proc. IEE 109, Pt. B, Suppl. 23, 693–695 (1962).*

Reflection coefficient measurements with reflectometer systems, *Hewlett-Packard Application Note No. 38, Sec. 4, pp. 25–28.*

VSWR measurements with slotted line, *Hewlett-Packard Application Note No. 38, Sec. 4, pp. 5–14.*

MICROWAVE REFLECTION COEFFICIENT
(PHASE ANGLE OF REFLECTION COEFFICIENT)

REFERENCE STANDARDS
  EXISTING CAPABILITY
  5 YEAR OBJECTIVE

CALIBRATION SERVICE
  EXISTING CAPABILITY
  5 YEAR OBJECTIVE

NON-NBS STATE OF THE ART

NBS

|Γ| = 0.01

|Γ| = 1.0

1 - 8 GHz (SLOTTED LINES)

8.2 - 12.4 GHz

PHASE ANGLE IN DEGREES

UNCERTAINTY (ONE PART IN)

98
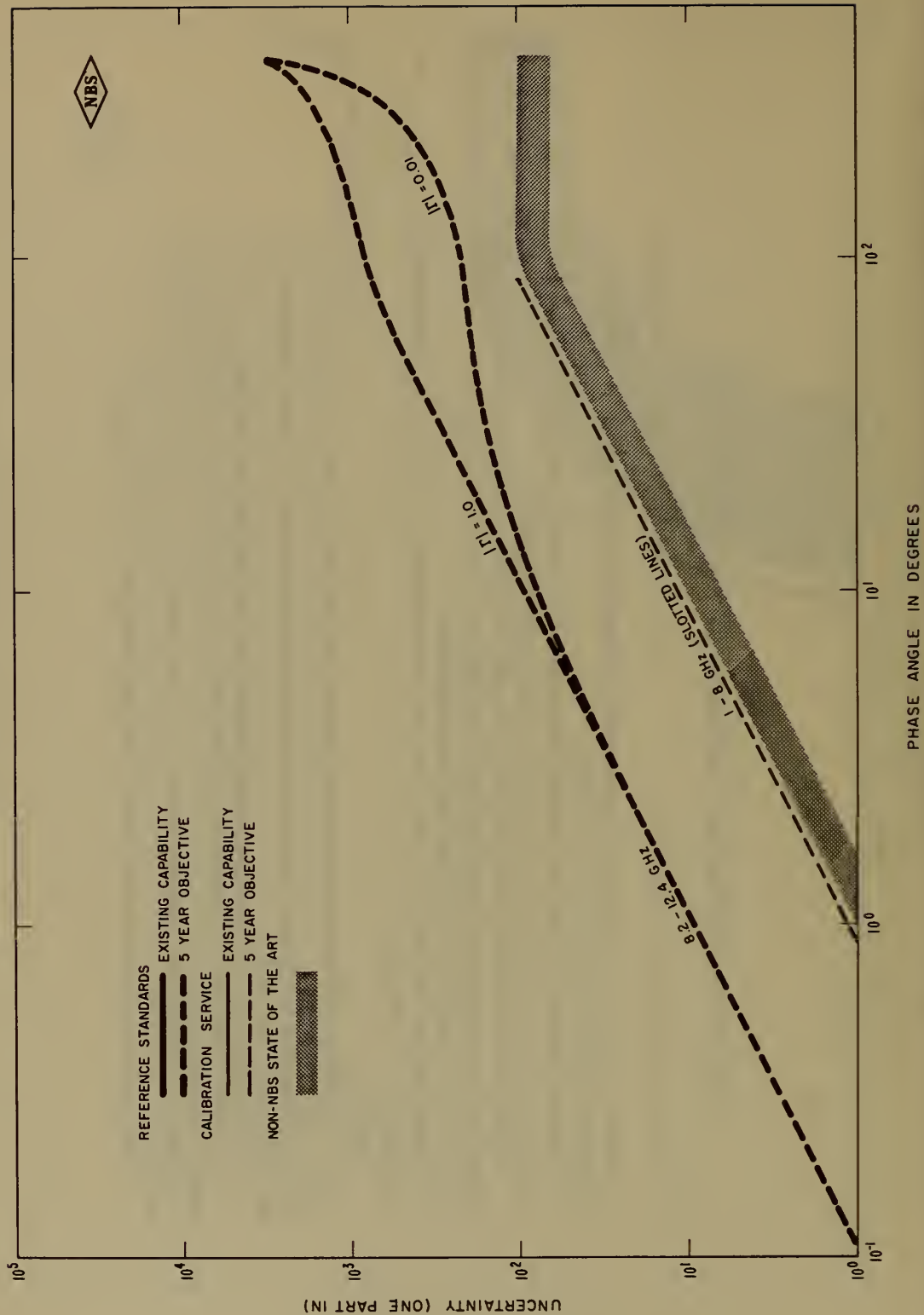
Microwave Reflection Coefficient (Phase Angle)

W. E. LITTLE, *Project Leader*, Standards   B. C. YATES, *Project Leader*, Dissemination

Five-year objective: The NBS five-year objective is based on the present work being done to combine reflectometer and phase-measurement techniques into a single instrument that will measure the complex reflection coefficient.

State of the art: The non-NBS state of the art band is based on slotted-line impedance-measuring techniques

References:
P. Lacy, Analysis and measurement of phase characteristics in microwave systems, *IRE WESCON Record (Aug. 1961)*.

P. Lacy, A versatile phase measurement method for transmission line networks, *IRE Trans. Microwave Theory Tech.* **MTT-9**, 568–569 *(Nov. 1961)*.

M. Magid, Precision microwave phase shift measurements, *IRE Trans. Instr.* **I-7**, 321–331 *(Dec. 1958)*.

S. B. Cohn, Swept phase-measurement techniques with CW and pulsed signals, *presented at International Conference of Precision Electromagnetic Measurements (Aug. 1962)*.

S. B. Cohn and H. G. Oltman, A precision microwave phase measurement system with sweep presentation, *IRE Convention Record, Pt. 3*, 147-150 *(Mar. 1961)*.

S. B. Cohn and N. P. Weinhouse, An automatic microwave phase measurement system, *Microwave J.* **7**, *No. 2*, 49–56 *(Feb. 1964)*.
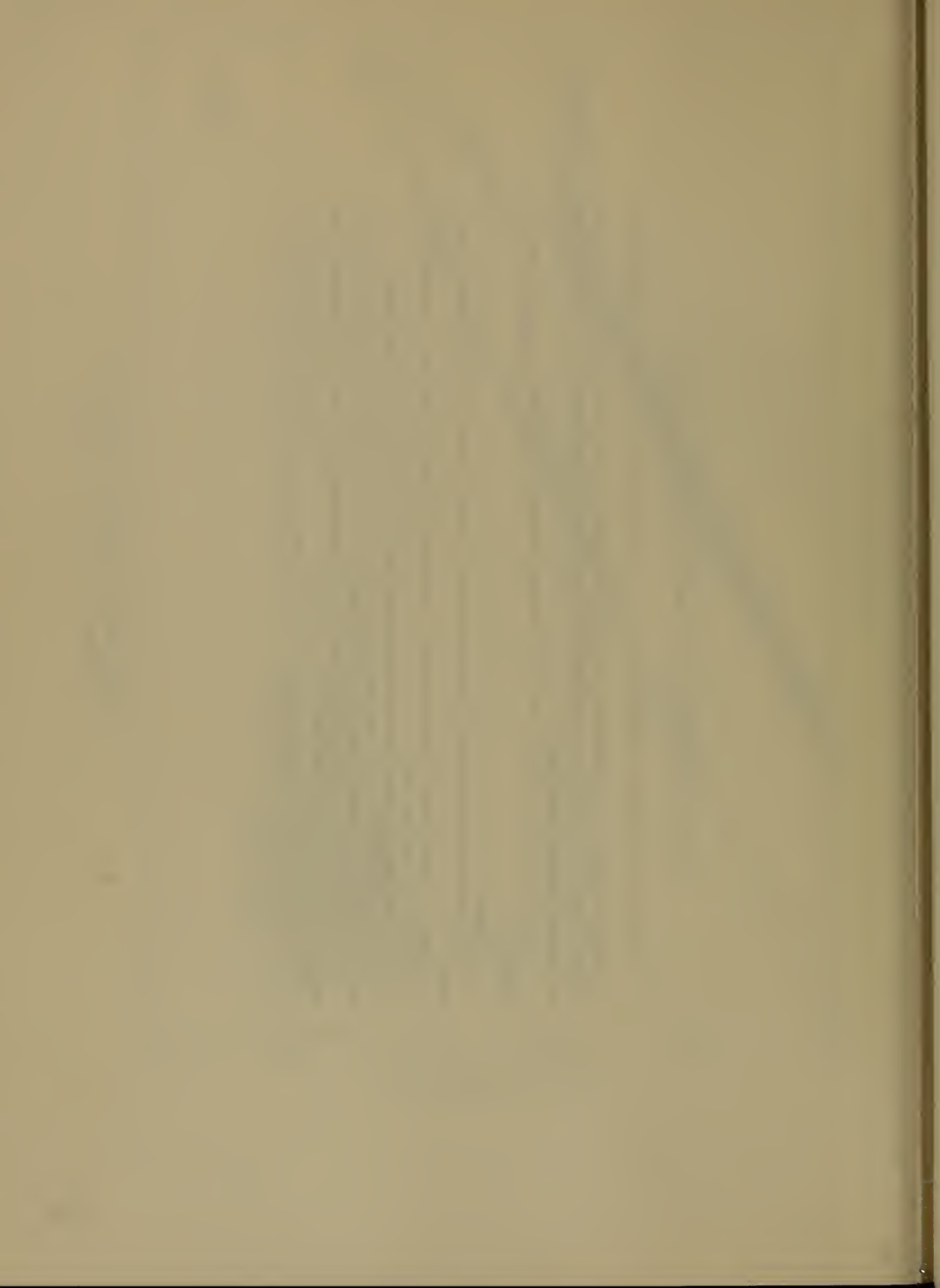
VI. Charts for Mechanical Quantities

PRECISION* OF ANGLE CALIBRATION
FOR MASTER ANGLE GAGE BLOCKS AND POLYGONS

NOTE: *BASED ON 3 STANDARD DEVIATIONS.
SYSTEMATIC ERRORS MAY BE OF THE SAME ORDER OF
MAGNITUDE AS THE PRECISION OF DETERMINATION.

ANGULAR MEASUREMENT BY
DIRECT INTERFEROMETRY

ANGLE GAGE BLOCKS BY
ANGULAR SUBDIVISION

POLYGONS BY COMPLETE
CIRCULAR CLOSURE.

NBS

DS 9/1/64
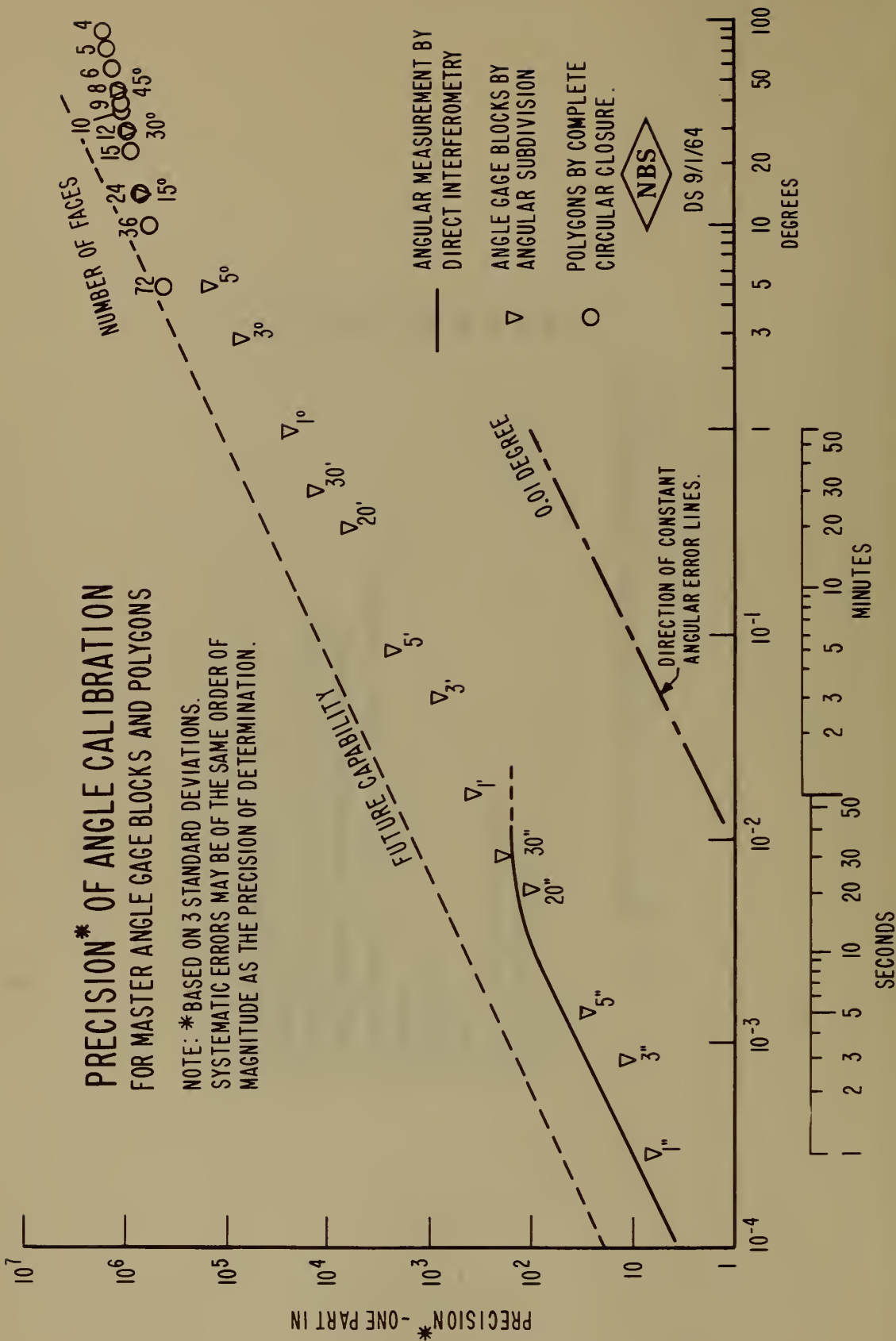
Angle

D. Spangenberg, *Project Leader*

State of the art: The NBS master angle gage blocks and polygons are measured either by summation to a full circle, or by the dimensional determination of trigonometric functions of the angle. Master angle blocks too small for circular closure to be practical are calibrated by a progressive sequence of angular subdivision of the larger masters, using interferometry and autocollimation techniques for the small angular differences involved. The precision shown on the chart is based on an estimated 3 standard deviations.

Working standards are calibrated by comparison, again using interferometry and autocollimation techniques.

Calibration service for angular measuring equipment is normally based on working gage blocks and polygons. The overall accuracy obtainable in determining an angle between defining faces is limited by their flatness, surface texture, and mutual perpendicularity to reference surfaces. Systematic errors resulting from this geometrical quality may be of the same order of magnitude as the precision.

Industry needs: In some cases polygons and angle gage blocks are used as a tool for the direct determination of a specific angle. In addition to the obvious requirements of the machine-tool industry, the space industry requires angle standards for accelerometer calibration, gyroscope evaluation, optical alinement, and space navigation.

Short-term objectives: Automation of polygon calibrations will permit the highest precision calibration by complete circular closure to be economically feasible. Development work is progressing to permit more precise comparison of angle blocks. Work is also being done to develop economically feasible techniques for the calibration of angle blocks by angular subdivision, and to develop highly accurate angle-generation instrumentation, as an aid in the calibration of nonstandard angles.

ACCURACY OF FLOW RATE MEASUREMENTS
NEAR ATMOSPHERIC CONDITIONS

104
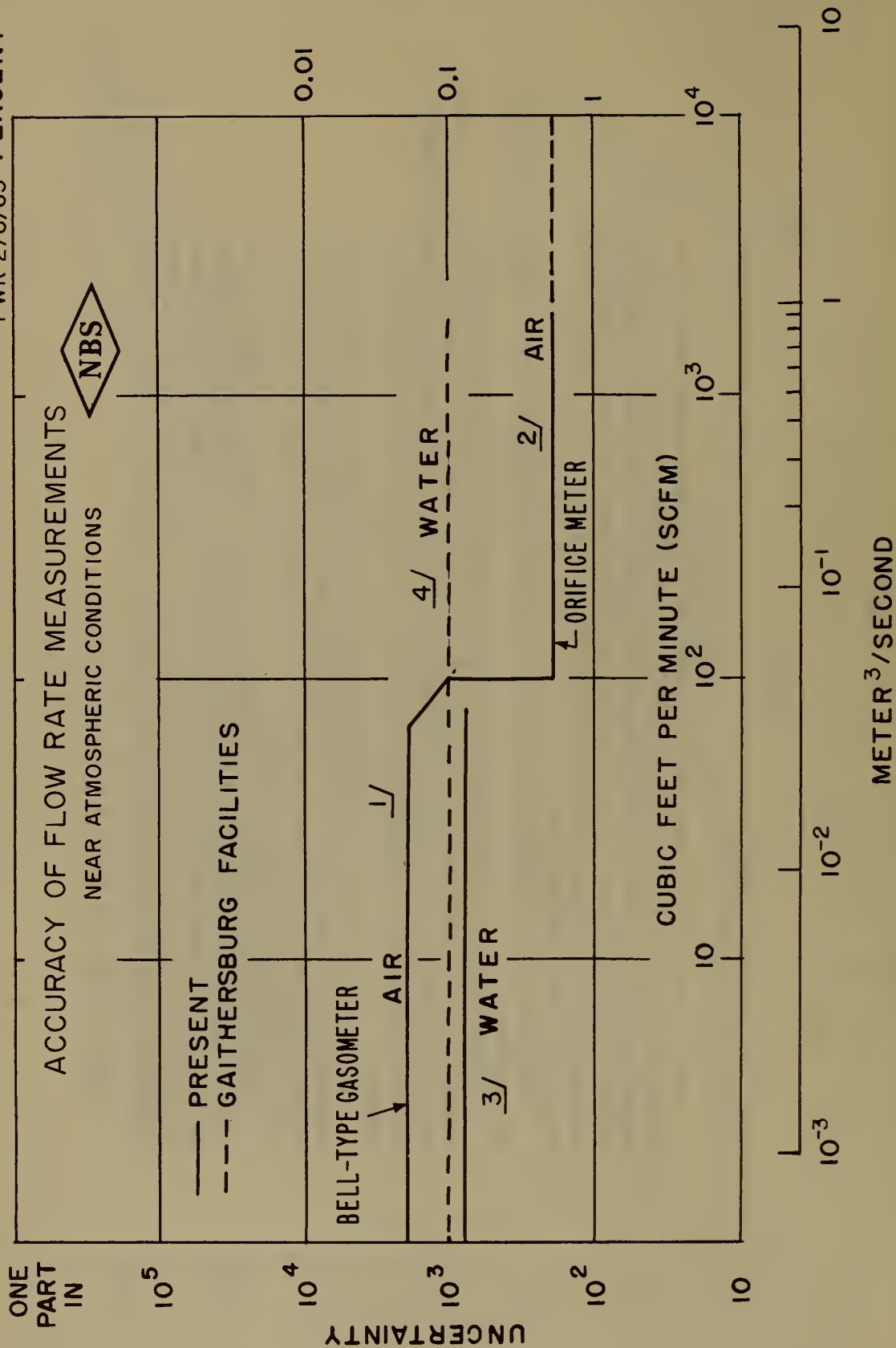
Flow—Air, Water

F. W. RUEGG, *Section Chief*

For air-flow measurement up to 100 cubic feet per minute (SCFM), bell-type gasometers are used as reference standards. Calibrations can be performed at elevated pressure, but volume rates of flow are based on laboratory temperature and pressure. For measurement of air flows between 100 and 2000 SCFM, orifice meters calibrated with water are used as reference standards. Pressure levels at the instrument being calibrated can be as high as 590 psi at the low rates and 50 psi at the high rates; temperature is generally that of the laboratory.

To measure the rate of flow of water, a static weighing procedure is used.

The uncertainty of 0.06 percent shown [1] for air rates below 100 SCFM is that of the NBS procedure for measurement of volume collected per unit time. Calibrations of meters of various types may show uncertainties of 0.3 percent or more as a result of meter instability. At rates above 100 SCFM, the uncertainty [2] increases to an estimated 0.5 percent because of using the orifice meter as a reference.

In calibration of water meters, the uncertainty shown [3] includes allowance for a systematic error of NBS procedure (0.05 percent), in addition to 3 standard deviations, where the standard deviation of the mean reported value is about 0.03 percent (for a relatively stable meter).

Industry need: A reference standard based on a weighing procedure for metering air and other gases at rates above 100 SCFM.

Short-term objectives: Study of improved reference standards to increase the accuracy of air flow measurement above 100 SCFM. Study of mercury-sealed piston provers as reference standards to attain an accuracy comparable to that above 1 SCFM. Installa- tion of new static-weighing equipment to increase the capability for water-flow measurement up to about 2000 CFM with an uncertainty of only 1 part in 1000.[4]

Reference:
T. J. Filban, Jr., and M. R. Shafer, Jr., ISA Preprint 12.2–4–64 (Oct. 1964).

References refer to correspondingly numbered areas on the chart.

LIQUID HYDROCARBON FLOWRATE STANDARDS

PRESENT
GAITHERSBURG FACILITIES

106
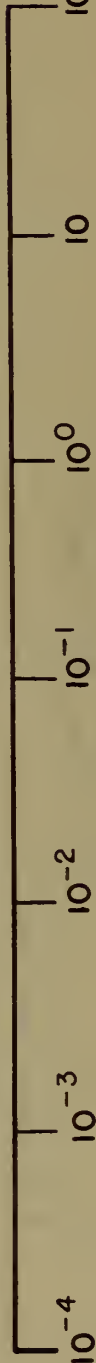
Flow—Liquid Hydrocarbons

M. R. SHAFER, *Project Leader*

State of the art: Static weighing procedure is available up to 25 gal/min; this is more accurate, but takes five times longer, than the established procedure of dynamic weighing which is used up to 200 gal/min. Liquids may have viscosities not exceeding 30 centistokes; and the requirement of venting to atmosphere limits vapor pressure to a maximum of 1 psia.

The uncertainty shown includes allowance for systematic errors of the NBS procedure, in addition to 3 standard deviations, where the standard deviation of the mean reported value ranges from 0.01 to 0.02 percent. Typical transfer reference meters add ±0.1 percent uncertainty under field use.

Industry need: Existing equipment supplied by BuWeps for fuels used by Navy, Air Force, NASA. Aircraft and missile industries mention 2000 gal/min, even 10,000 gal/min.

Short-term objectives: Study of new metering methods; also of performance and reliability of aircraft fuel systems. Installation at Gaithersburg of 3000 gal/min static weighing facility with estimated uncertainty of only ±0.07 percent.

Reference:
  T. J. Filban, Jr., and M. R. Shafer, Jr., ISA Preprint 12.2–4–64 (Oct. 1964).

ACCURACY OF FORCE MEASUREMENT

LKI 8/11/64

Force

L. K. IRWIN, *Section Chief*
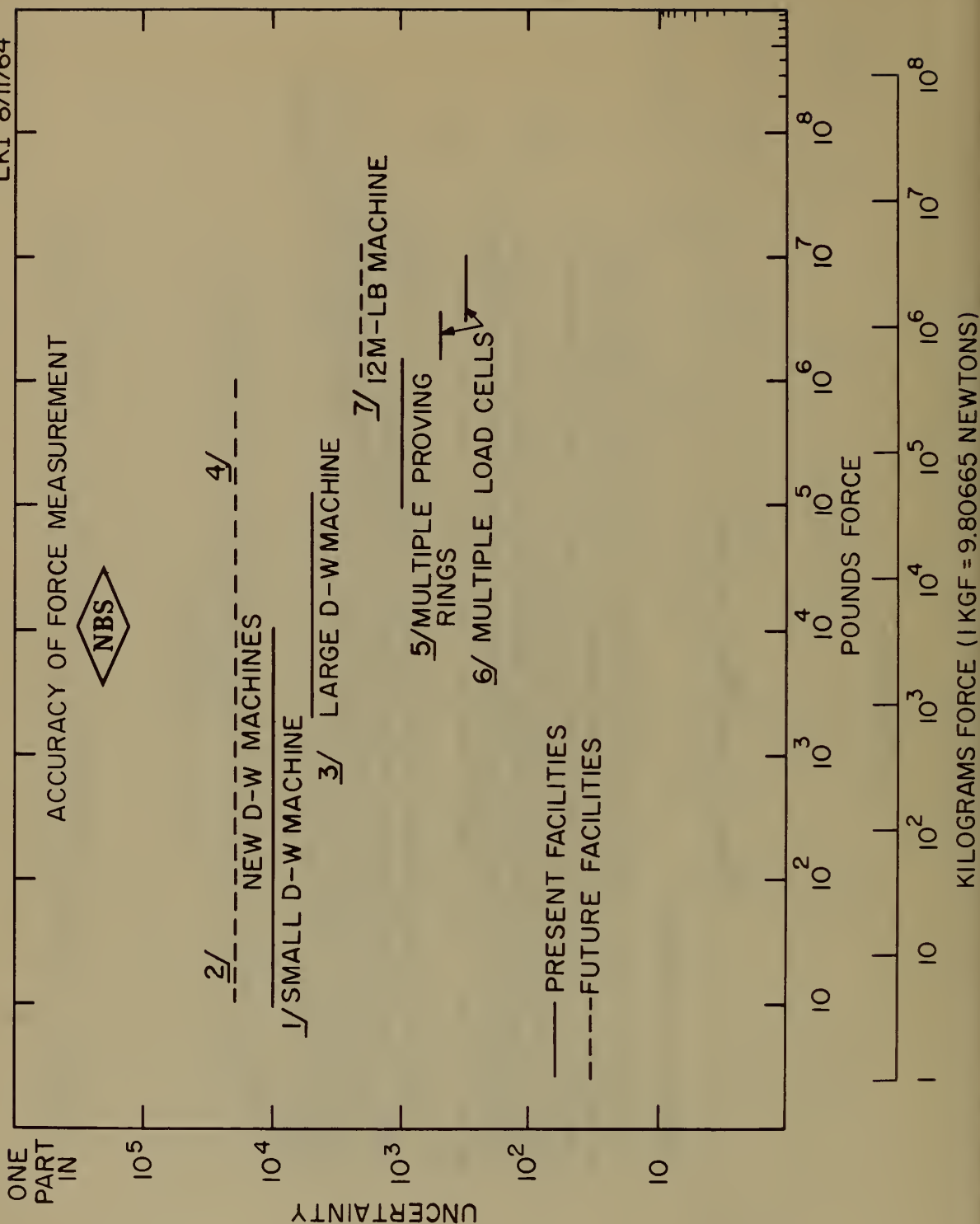
State of the art: The uncertainty shown includes an allowance for systematic errors involved in adjusting individual weights on machines. Curves are shown as straight lines plotted to show maximum uncertainty for the range because sufficient work has not been done to determine the extent to which accuracy is better over some portions of the ranges. Proving ring reports [5] are computer-processed. Contract has been let for 12-million-lb machine.

Industry needs: Aerospace Industry Association surveys, Air Force contractors: Space mission boosters for 25 million lb approved, 100 million lb considered. Users of calibration services: Steady increase since 1942 from 100 to 900 per year.[1,3,5,6] International comparison: Local value of *g*.

Short-term objectives: Complete installation of 112,000-, 300,000-, and 1,000,000-lb machines.[2,4] Monitor contractor and install 12-million-lb machine.[7] Study dynamic response of transducers. Improve 0.015 sec rise time of 10,000-lb transient force generator. Study errors of calibration with devices in parallel.[5,6] Study errors in transfer calibrating. Complete determination of *g*. Study feasibility and develop calibration techniques for handling 30 million lb. Extend transient range to 100,000 lb. Study environmental effects on calibrations.

References refer to correspondingly numbered areas on the chart.

FIXED POINTS - SATURATED
SALT SOLUTIONS

○ 0°C
+ 50°C

CAPABILITY
OF
NBS HUMIDITY STANDARDS
WITH ATMOSPHERIC AIR AT
ATMOSPHERIC PRESSURE

MIXING RATIO, GRAMS WATER VAPOR / KILOGRAM AIR

UNCERTAINTY

ONE PART IN

NBS STANDARD (GRAVIMETRIC) HYGROMETER

NBS TWO-PRESSURE HUMIDITY GENERATOR

NBS PNEUMATIC BRIDGE HYGROMETER

DEW POINT, °C   AW 8/7/64

FROST POINT, °C

K_2SO_4 (95.8 % RH)
KNO_3 (85.0 % RH)
$NaCl$ (74.7 % RH)
$(NH_4)_2SO_4$ 79.1 % RH)
$Mg(NO_3)_2$ (46.3 % RH)
$MgCl_2$ (31.4 % RH)

$LiCl$ (11.4 % RH)

K_2SO_4 (99.1 % RH)
KNO_3 (97.6 % RH)
$(NH_4)_2SO_4$ (83.7 % RH)
$NaCl$ (74.9 % RH)
$Mg(NO_3)_2$ (60.6 % RH)

$MgCl_2$ (35.0 % RH)

$LiCl$ (14.7 % RH)

Humidity

A. WEXLER, *Section Chief*

State of the art: Moisture content of air is measured by the NBS Standard Hygrometer to an accuracy within 1 part in 8×10^2 (1.3 parts in 1000) over the mixing ratio range of 0.15 to 20 g/kg. The NBS Two-Pressure Generator can produce an atmosphere of air of known mixing ratio from 0.15 to 20 g/kg to within 1 part in 2×10^2 (5 parts in 1000). Over the mixing ratio range of 0.0015 to 0.15 g/kg the uncertainty is 0.00075 g/kg; the equivalent minimum frost point produced is -70 °C. Saturated salt solutions produce fixed points of relative humidity from 12 to 98 percent over an ambient temperature range of 0 to 50 °C, corresponding to mixing ratios of 0.55 to 78 g/kg. Moisture content of air is measured by the NBS Pneumatic Bridge Hygrometer over mixing ratios of 0.15 to 20 g/kg to within 0.05 g/kg. The uncertainties given above and in the chart include 3 standard deviations plus systematic errors.

Industry needs: The measurement and control of humidity play an important role in many aspects of the work in such scientific disciplines as physics, chemistry, biology, and medicine; in many branches of engineering; in meteorology and in agriculture; and in such diverse industrial fields as air conditioning, drying, refrigeration, cryogenics, storage, food processing, packaging, materials manufacturing and processing, natural gas transmission, compressed gases, and electronics. There is a current need for extending the calibration capability to both lower and higher moisture contents.

Short-term objectives: (1) To extend the range of the NBS Standard Reference Hygrometer to cover mixing ratios down to 0.02 g/kg to within 1 part in 8×10^2. (2) To improve the NBS Two-Pressure Humidity Generator accuracy to an uncertainty within 2 parts in 1000 over the mixing ratio range of 0.15 to 20 g/kg; to improve it to within 5 parts in 1000 over the mixing ratio range of 0.0015 to 0.15 g/kg. (3) To provide more closely spaced fixed points (every 5 percent RH) by means of saturated salt solutions and to extend the usable ambient temperature range for saturated salt solutions to cover -20 to 90 °C.

PRESSURE MEASUREMENT

112
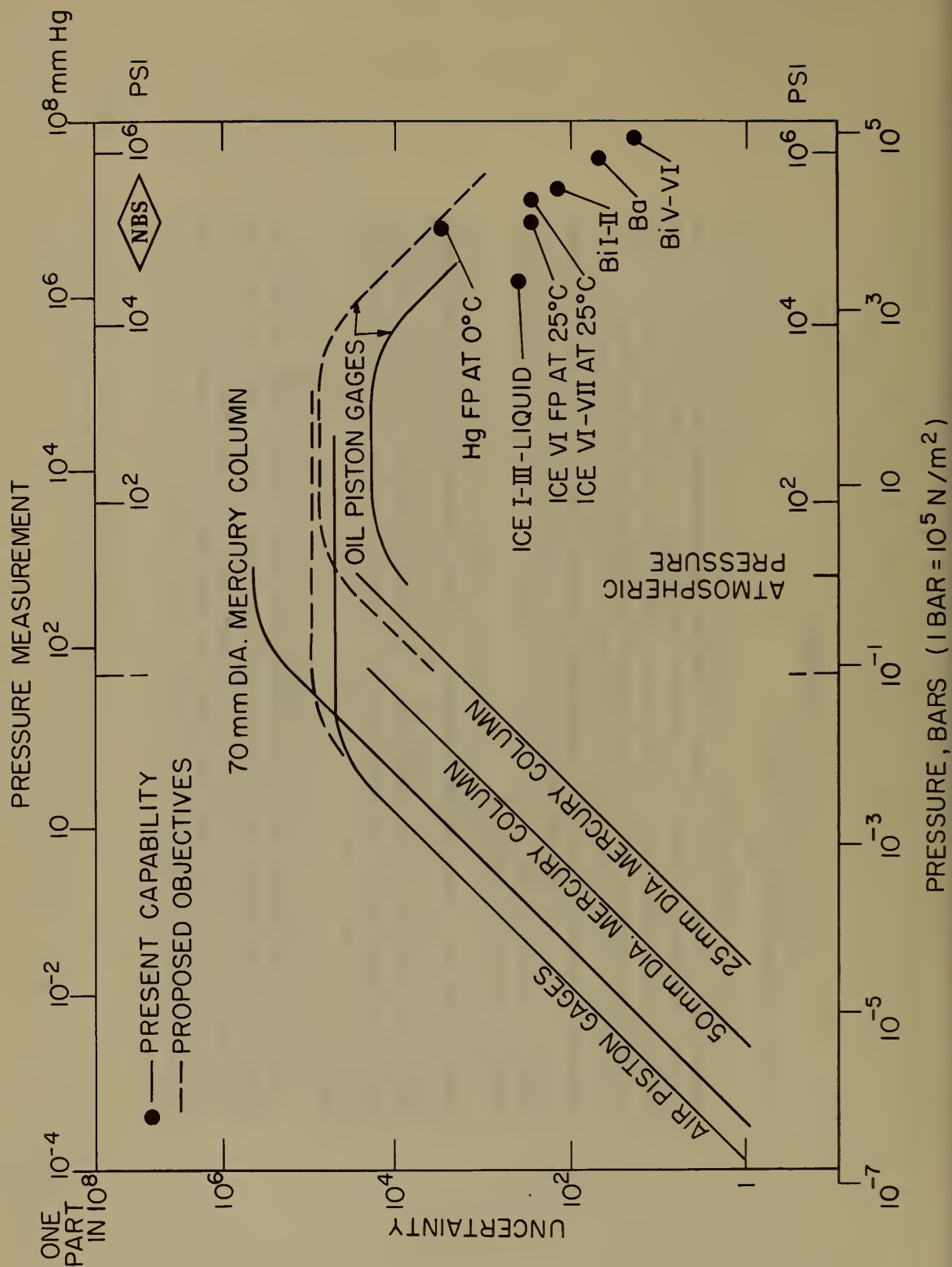
Pressure

E. C. Lloyd, *Branch Chief*

In the estimate of accuracy shown, the uncertainty of the absolute value of gravity was excluded. (This is significant only in the 70-mm-diam mercury column for which the most important use was the determination of pressure ratios.) An attempt was made to estimate other systematic errors. In the rising part at the low-pressure end of the curves, the uncertainty was dominated by least count or readability errors, by uncertainties associated with a liquid-gas interface, etc. At high pressures the elastic distortion errors dominate; for these the percentage error is proportional to the pressure. The NBS calibration service is bounded in accuracy and range by the solid-line curves shown for the air and oil piston gages. Other standards are used as appropriate, but do not exceed the capabilities of these instruments. Calibration service is available at 8 kilobars (120,000 psi), using the first of a new generation of piston gages of improved accuracy.

A very large fraction of all mechanical measurements is concerned with pressure. In the chemical industry the yield, uniformity, and quality of the product depend in part on precise measurement and control of the pressure. Many of the demands for increased accuracy and range come from the aerospace industry. Air pressure at an altitude of 95,000 ft is about 10 mm mercury. At an ocean depth of 20,000 ft, the pressure is 10,000 psi. Pressures well over 10^6 psi are important in geology, in the study of properties of materials, and in some industrial processes.

AUDIOMETRIC EARPHONE RESPONSE
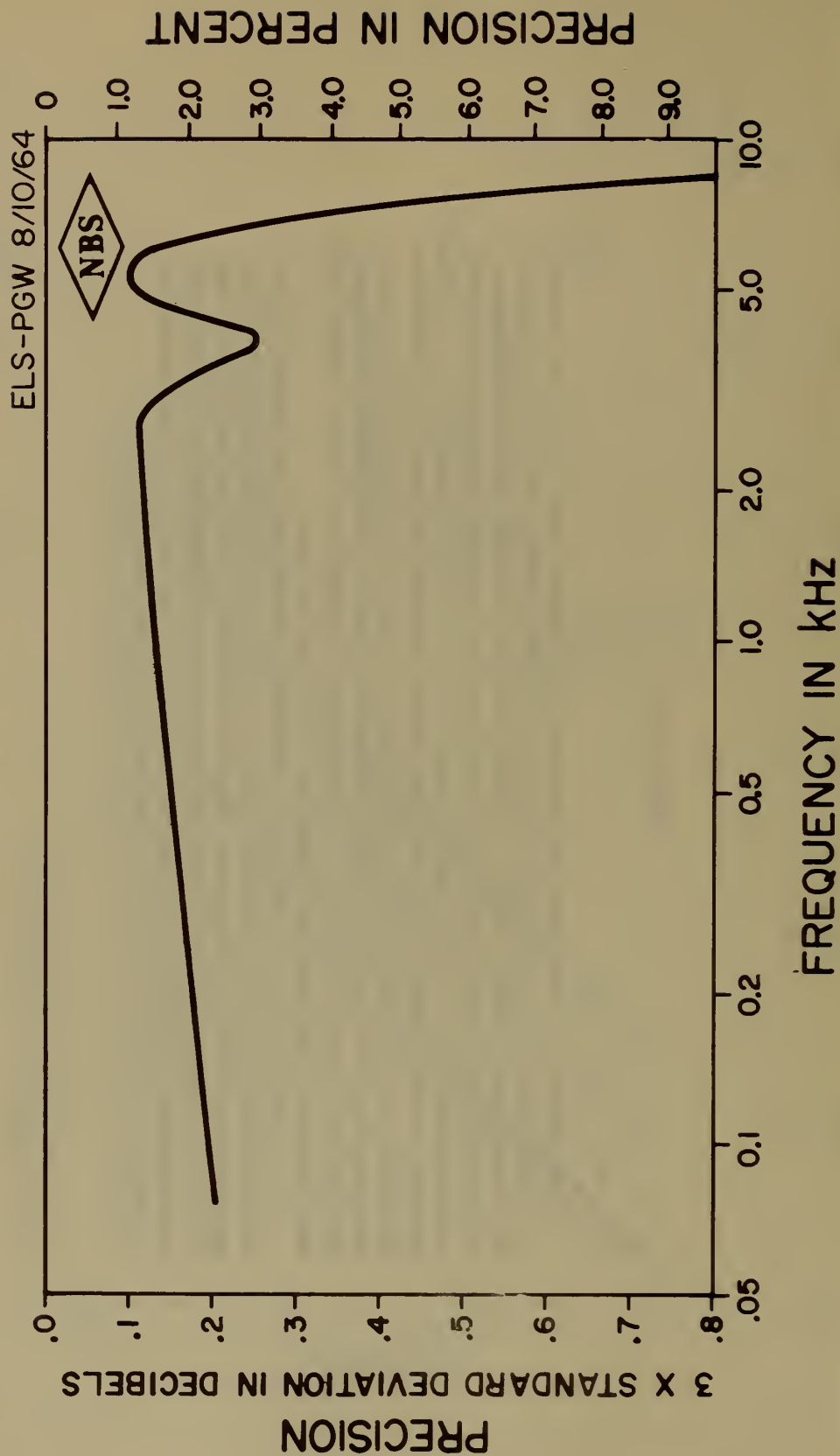
Audiometric Earphone Response

P. G. WEISSLER, *Project Leader*

Calibration of an audiometric earphone is the measurement of the sound pressure P generated by the earphone in a specified volume for a given driving voltage E. The response of the earphone is defined as $20 \log_{10}(P/E)$ dB. The volume used is the 5.64-cm³ NBS Type 9A Coupler* terminated by a Western Electric Company Type 640AA condenser microphone whose response is known.

The precision of the earphone response depends upon equipment stability and the positioning of the earphone on the coupler. The precision shown is based on 11 calibrations of a Western Electric Company Type 705A earphone, and drops to 2.1 dB at 10 kHz. The estimate of credible bounds to the systematic error is 0.25 dB. Systematic errors were estimated from such factors as uncertainties in the coupler volume, uncertainties in the impedance and response of the microphone, and the calibration of the attenuators. The voltage applied to the earphone during calibration is approximately 10 mV; changes as much as several millivolts have a negligible effect on the accuracy of calibration.

Short-term objectives: Extending the range of calibrations to at least 12 kHz; improving the precision of the calibrations at 8 kHz and above.

American Standard Specification for Audiometers for General Diagnostic Purposes, Z24.5–1951.

PRECISION IN PERCENT

PRECISION

3 X STANDARD DEVIATION IN DECIBELS

FREQUENCY IN kHz

WK-IJR 8/10/64

NBS

20cm³ COUPLER

38cm³ COUPLER

PRECISION
for
CONDENSER MICROPHONE RESPONSE
to
SOUND PRESSURE

116
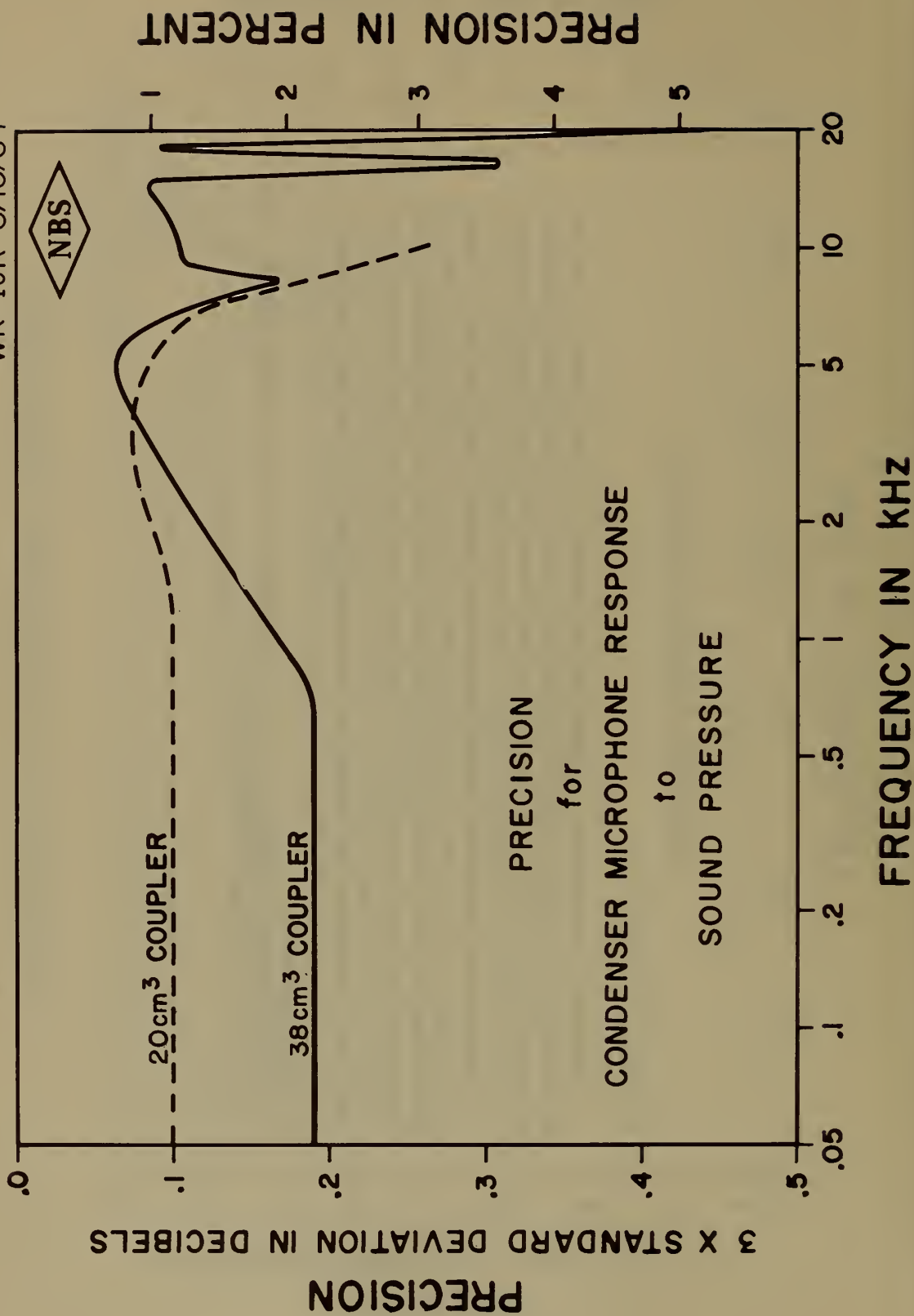
Condenser Microphone Response to Sound Pressure

W. KOIDAN, *Project Leader*

The pressure response of a microphone at a single frequency is defined as $20 \log_{10} (E/P)$ dB, where E is the open-circuit voltage of the microphone for a sound pressure P, applied uniformly over the exposed surface of the diaphragm.

Pressure calibrations are performed in closed couplers by comparison with Western Electric Company Type 640AA condenser microphones calibrated by the reciprocity technique as described in American Standards Association Standard Z24.4–1949. The sound pressure during calibration is in the range of approximately 1 to 10 dynes/cm^2; in that range, changes in sound pressure have a negligible effect on accuracy.

The precision is plotted as 3 times the standard deviation calculated from recent calibration test data. The estimates of credible bounds to the systematic error are as follows:

Coupler volume	Frequency range	Estimated systematic error
20 cm^3	0.05 to 10 kHz	0.07 dB.
3.8 cm^3	0.05 to 20 kHz	0.11 dB.

Short-term objectives: Extension of the frequency range to higher and lower frequencies; extension of calibrations to higher sound intensities.

PRECISION IN PERCENT

WK-1JR 8/10/64

NBS

PRECISION
for
MICROPHONE RESPONSE
to
FREE FIELD SOUND PRESSURE

FREQUENCY IN kHz

3 X STANDARD DEVIATION IN DECIBELS

PRECISION

118
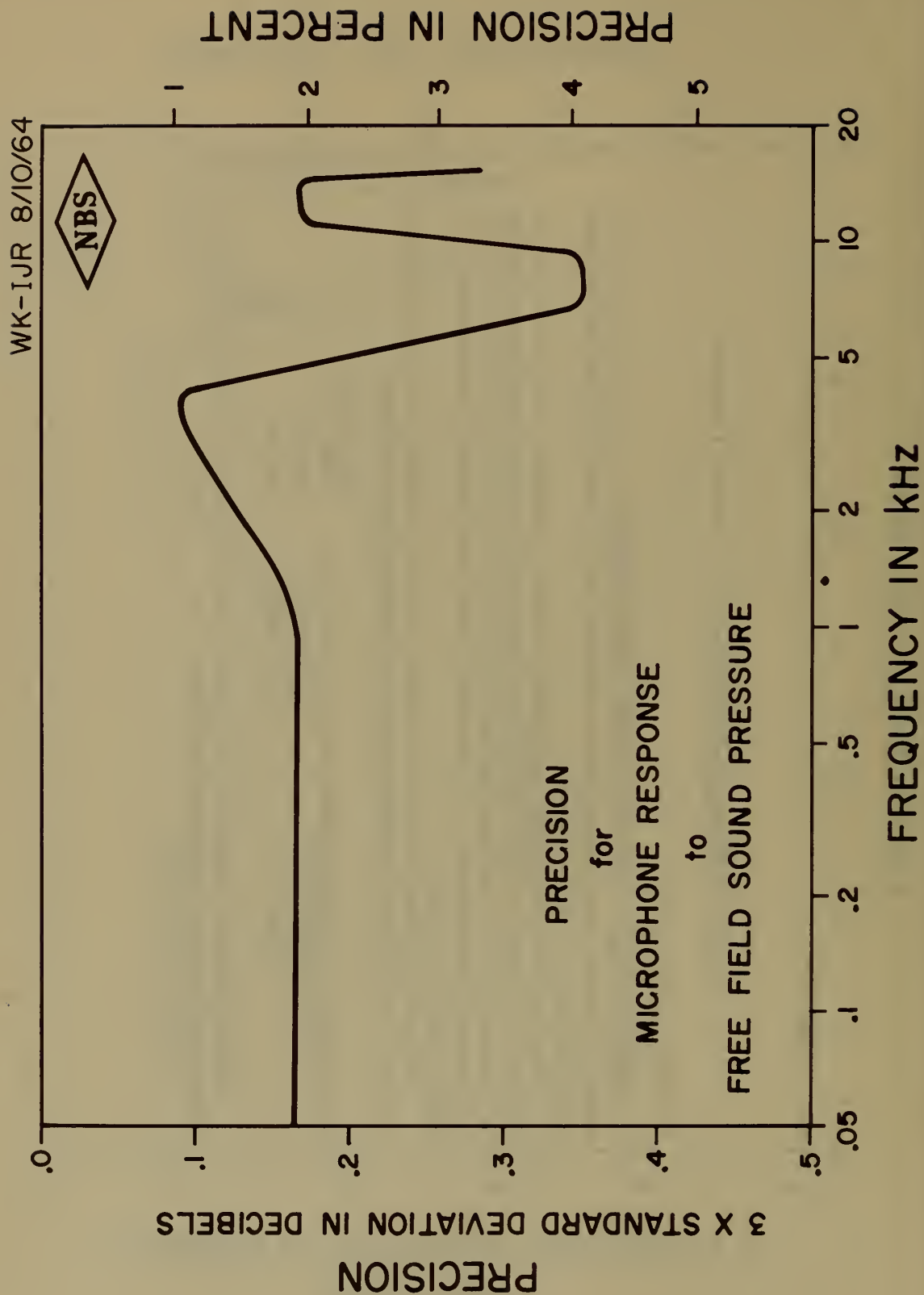
Microphone Response to Free-Field Sound Pressure

W. KOIDAN, *Project Leader*

The free-field response of a microphone at a single frequency and specified orientation with respect to the direction of sound propagation is defined as $20 \log_{10}(E/P)$ dB, where E is the open-circuit voltage of the microphone and P is the sound pressure in the plane-progressive sound wave which existed at the location of the microphone prior to the introduction of the microphone into the sound field.

Free-field calibrations are performed in an anechoic chamber by comparison with Western Electric Company Type 640AA condenser microphones calibrated by the free-field reciprocity technique. Sound pressure during calibration is in the range of approximately 1 to 10 dynes/cm²; in that range changes in sound pressure have a negligible effect on accuracy.

The precision is plotted as 3 times the standard deviation calculated from recent calibration test data. These estimates of precision and systematic error apply for sound propagation perpendicular to the plane of the microphone diaphragm. The estimates of credible bounds to the systematic error are as follows:

Frequency range	Estimated systematic error
0.05 to 5 kHz	0. 1 dB
6 to 15 kHz	0. 2 dB

Short-term objectives: Improvement of accuracy by the development of more stable sound sources; extension of the frequency range to higher and lower frequencies; extension of calibration work to higher sound intensities.

NBS VACUUM STANDARDS

EXISTING ————
UNDER DEVELOPMENT — — —
POTENTIAL + + + +

120
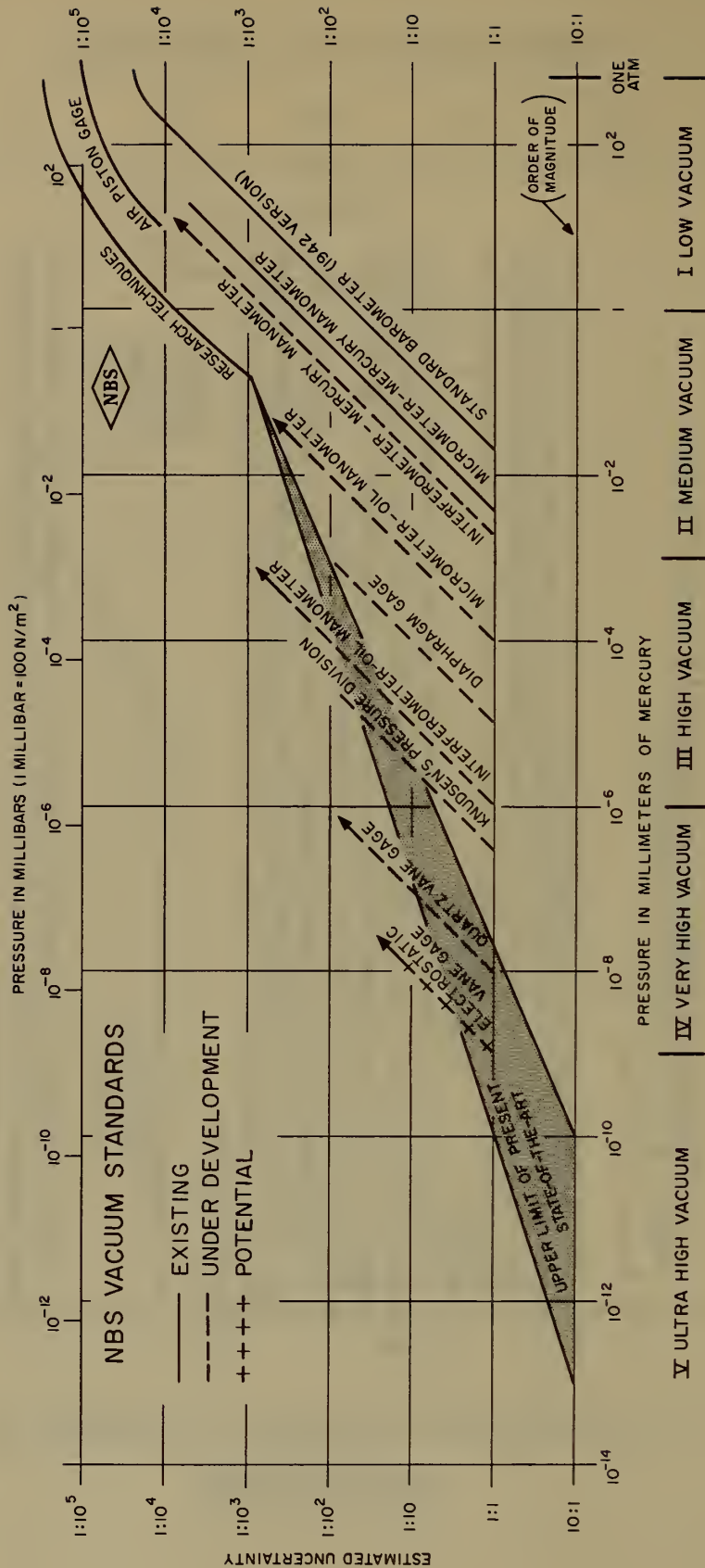
Vacuum

S. Ruthberg, *Section Chief*

Direct measurement of force per unit area has an uncertainty of 1 part in 100,000 at atmospheric pressure to a few percent at 1×10^{-3} mm Hg. The grey zone represents estimated measurement accuracy in the vacuum region (McLeod gage: Moser and Poltz—PTB at 1×10^{-6}) extrapolated to ultra-high range by Nottingham (MIT) and by Redhead (NRC Canada). Devices for the range below 1×10^{-9} are essentially particle counters, where measured values must be related to pressure. Between 1×10^{-10} and 1×10^{-17} mm Hg, quantitative measurements have been reported, but accuracy is no better than an order of magnitude.

The following are examples of industrial and scientific work involving pressures in the various ranges represented on the chart.

Regions I–II—altitude and airspeed of aircraft, vertical separation of aircraft;

Region II—process control, freeze drying, vacuum melt of steel, inflation pressure of balloon-type satellites;

Regions I to V—space simulation, environmental test;

Regions III to V—electron devices, high-energy accelerators;

Regions I to V—plasma physics;

Regions III to V—vacuum metallurgy, semiconductors, refining of metals, evaporated films, microcircuitry.

VELOCITY: ACCURACY OF AIR-SPEED MEASUREMENT
FOR CALIBRATION OF WIND-SPEED INDICATORS

122
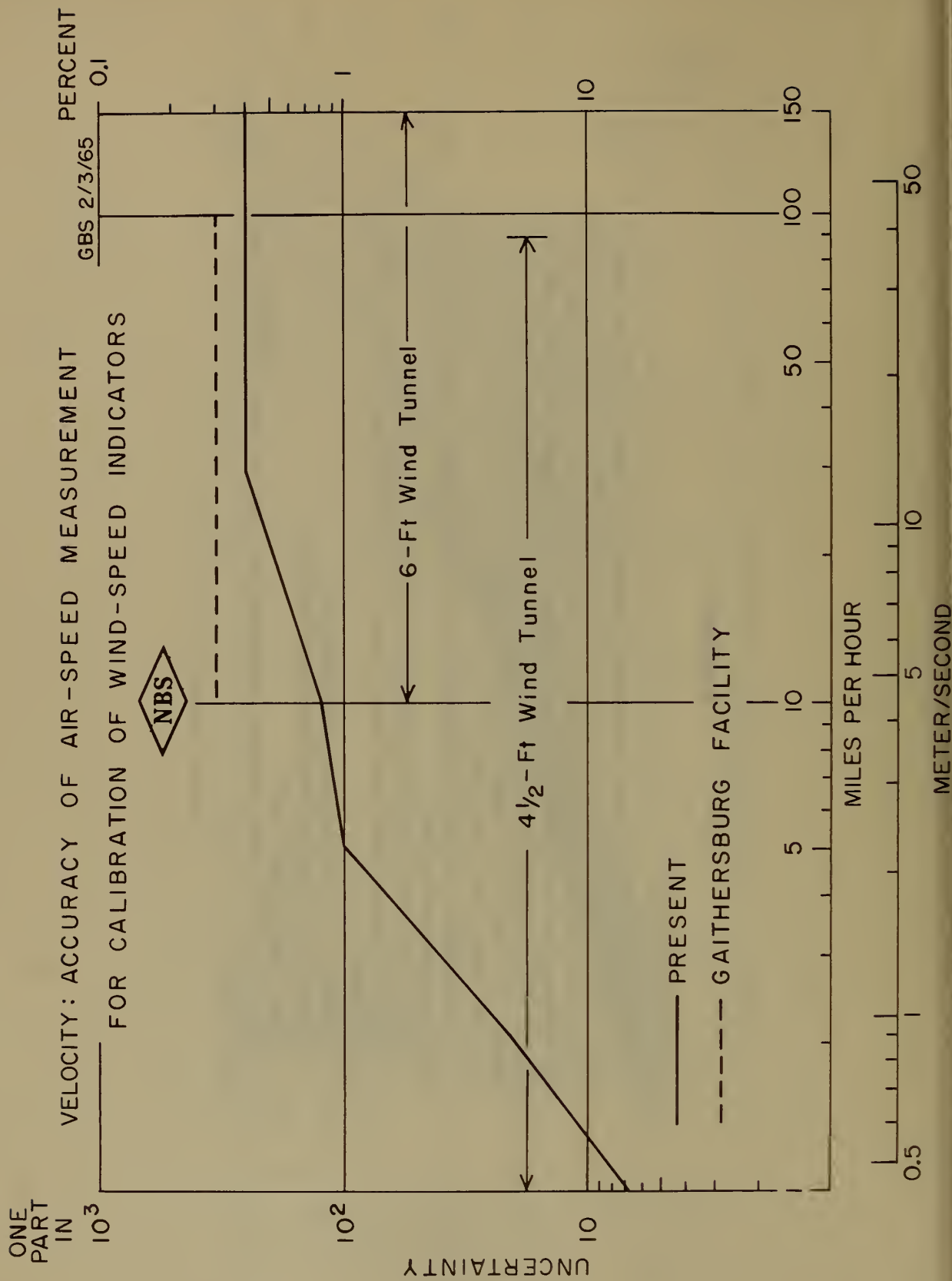
Velocity (Calibration of Wind-Speed Indicators)

G. B. Schubauer, *Section Chief*

The standard is the pitot-static tube, so designed that the differential pressure for incompressible flow departs from dynamic pressure by no more than ±0.2 percent. The corresponding uncertainty in air speed is ±0.1 percent if the compressibility of air is taken into account. Since compressibility effects are taken into account where significant, this ±0.1 percent uncertainty serves, when combined with that of other quantities involved, to give the total estimated uncertainty shown on the chart. The difficulties inherent in reading low differential pressures account largely for the decreasing accuracy with decreasing speed.

While increased accuracy would be desirable over the whole range, it is definitely needed below 10 mph. However, not much improvement can be expected in present facilities. The Gaithersburg facility will afford an opportunity for improvement, but the amount to be expected below 10 mph cannot be predicted at present.

123
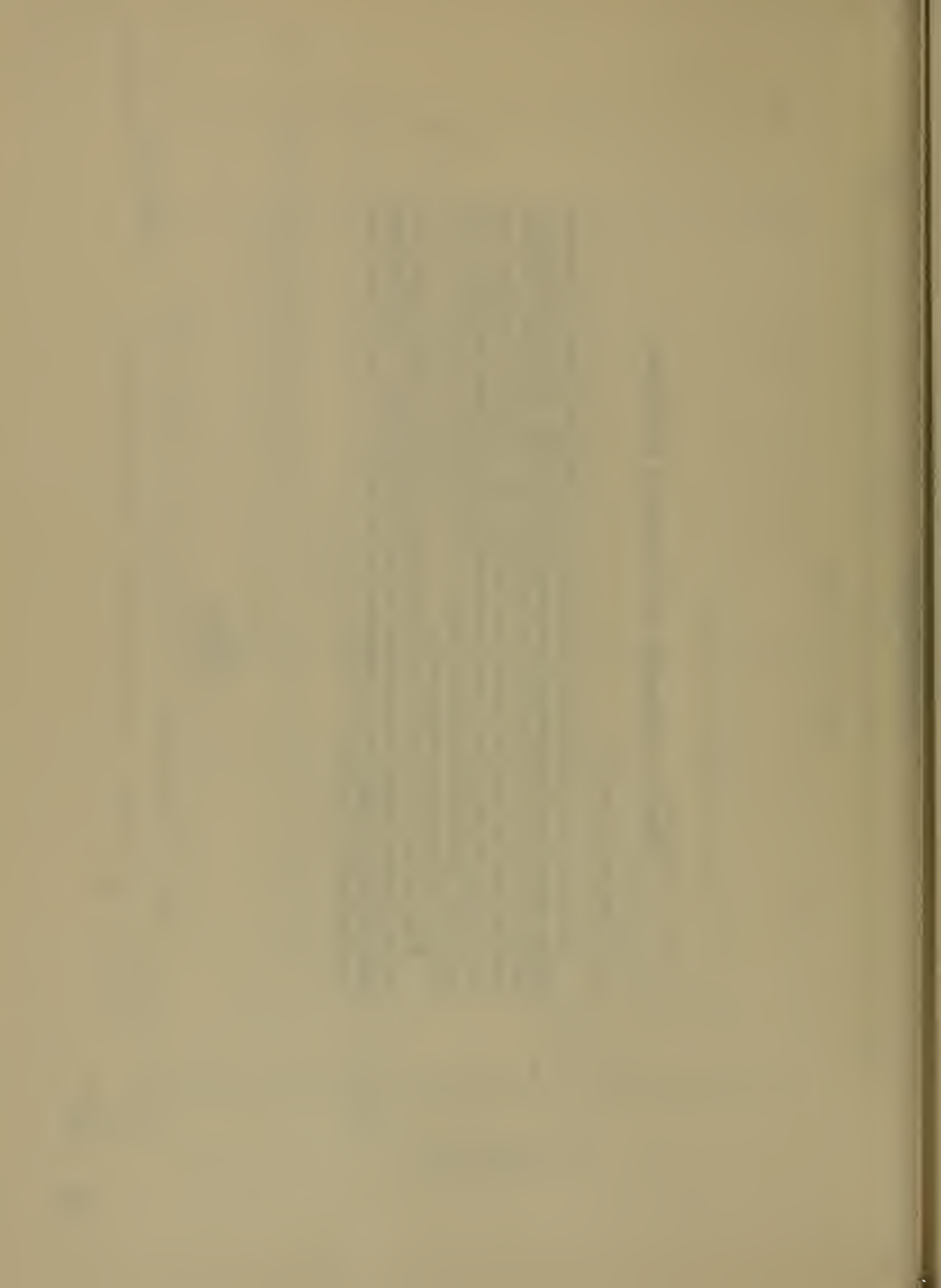
VII. Charts for Optical and Ionizing Radiation

125

SPECTRAL RADIANCE CALIBRATIONS

HJK 12/30/64

NBS

PRESENT CAPABILITIES
PROPOSED OBJECTIVES

ONE PART IN

ESTIMATED UNCERTAINTY

WAVELENGTH IN MICRONS

PERCENT

126

Spectral Radiance

H. J. KOSTKOWSKI, *Project Leader*

State of the art: The uncertainty of spectral radiance calibrations has until recently been about 3 percent at 0.8μ and 8 percent at 0.25μ—larger than that of almost any other widely used physical quantity. The NBS reference standards are based on the rate of energy emission of a laboratory blackbody, which varies with wavelength and absolute temperature according to Planck's law. Their accuracy depends upon the degree of approximation to blackness and the accuracy of temperature measurement of the blackbody used as primary standard, and also upon the long-term stability of secondary sources of radiation, such as tungsten strip lamps, which serve as comparators.

Improvement in these factors has been achieved with the development of a new spectroradiometer at NBS. The chart curves above 0.3μ (300 nm) apply to a tungsten strip lamp operated at a brightness temperature of about 2500 °K at 0.65μ with a radiance of 1.47×10^5 W cm^{-3} steradian^{-1}; below 0.3, to a lamp operated at about 2675 °K at 0.65μ. The uncertainty shown is an estimate based on probable sources of systematic error; imprecision is negligible.

Industry needs: Spectral radiance calibrations below 0.8μ (800 nm) already achieved with the new spectroradiometer are adequate for the present, and the uncertainty of 0.6 to 1.7 percent shown by the solid line above 0.8μ is expected in 1965.

Short-term objectives: To develop techniques for improving the long-term stability of secondary sources of radiation, such as tungsten strip lamps.

CALIBRATION FOR SPECTRAL IRRADIANCE STANDARDS

128
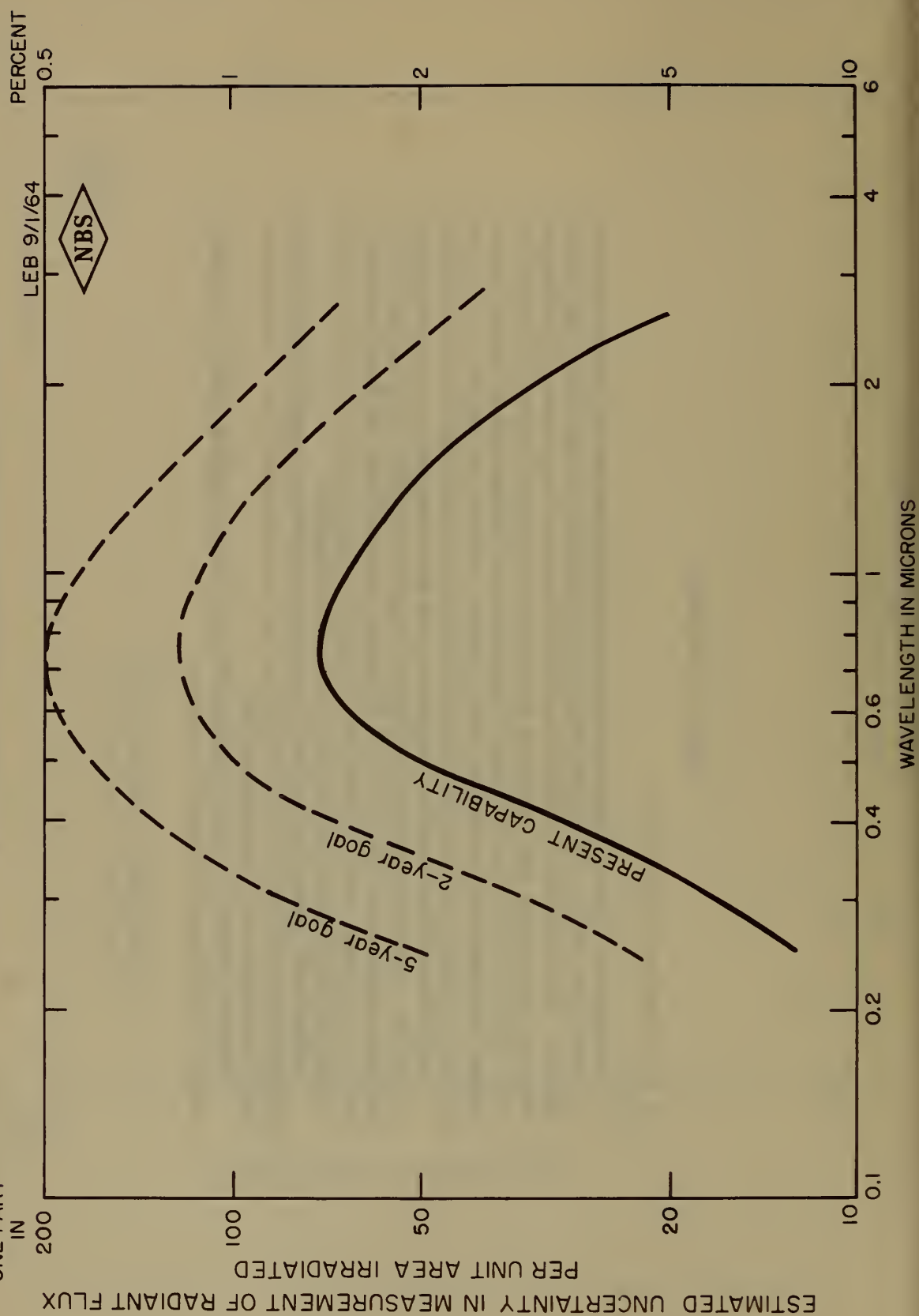
Spectral Irradiance

R. STAIR, *Project Leader*

State of the art: The NBS reference standards of spectral irradiance are based upon the spectral radiance (rate of energy emission) of a blackbody (which varies with wavelength and absolute temperature according to Planck's law). Their accuracy depends upon the uniformity of temperature and the degree of approximation to blackness of the laboratory blackbodies used as primary standards and the accuracy of measurement of this temperature, and also upon the accuracy, with the available instrumentation, of the comparisons with the laboratory blackbodies. Although the numerical range of radiant flux depends on the inverse square of the distance between source and detector, the effect on measurement uncertainty is less than that of wavelength and the chart is accordingly plotted on a wavelength base. The relatively low accuracy at both short and long wavelengths results principally from the relatively low radiances and irradiances involved, but is accentuated at short wavelengths by the greater effect of temperature-measurement uncertainty.

Industry needs: In connection with space and health research, accuracies are needed—primarily in the ultraviolet (below 0.4μ)—perhaps five times better than those now available.

Short-term objectives: To increase accuracy in two steps: first, by making comparisons of the standards relative to laboratory blackbodies with a new photoelectric pyrometer, a step which is expected to reduce the present uncertainty by a factor of about 2; second, by making use of an absolute radiometer which can be calibrated directly in terms of electrical power input, the present uncertainty may be reduced by a factor of 5 or more at both short and long wavelengths, if calibrations are made for sources of higher spectral output than those presently supplied.

ACCURACY of WAVELENGTH MEASUREMENT

KGK 3/25/64

130
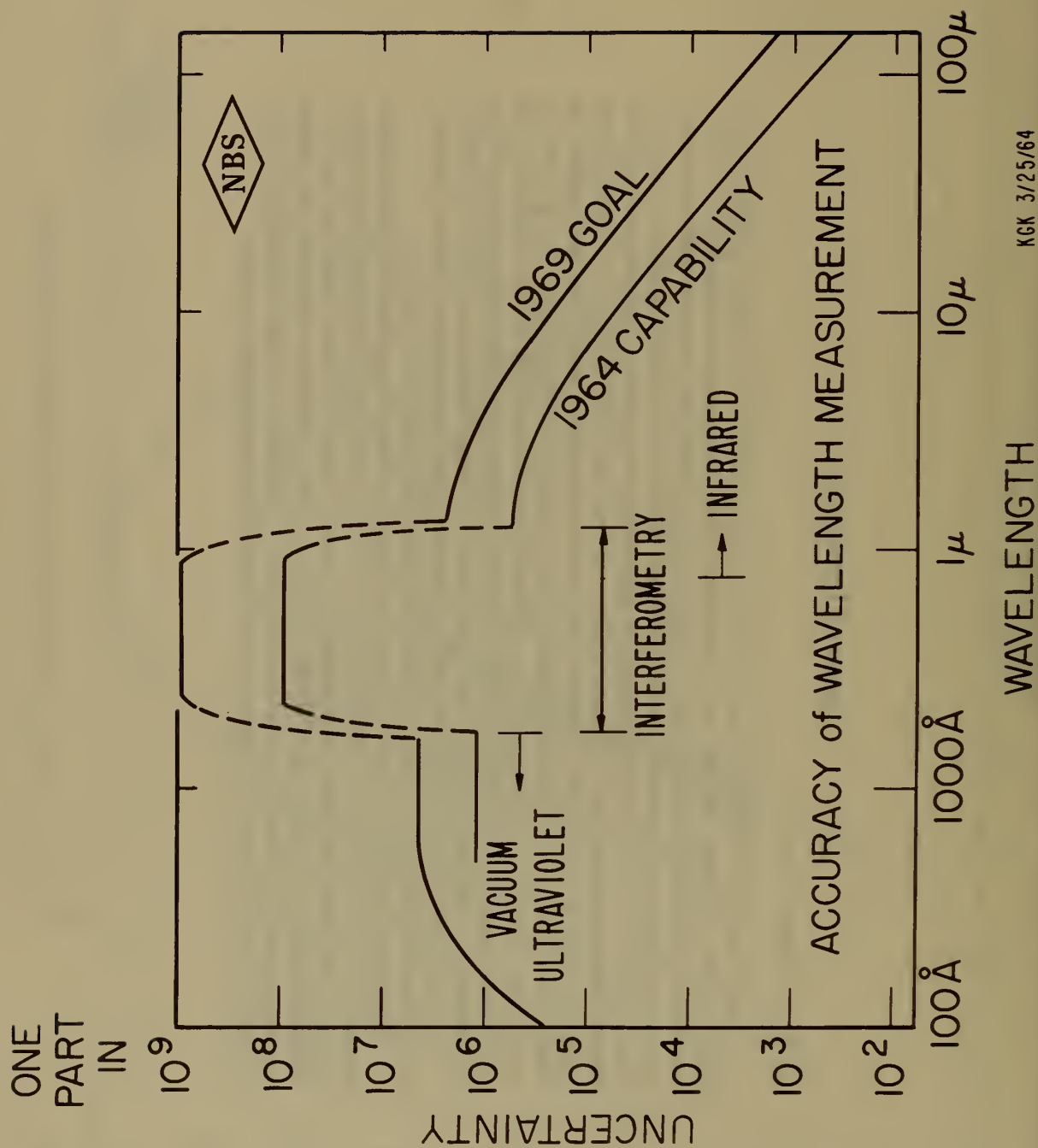
Wavelength Standards

K. G. KESSLER, D. R. LIDE, J. B. MARTIN, *Section Chiefs*

State of the art: The most accurate wavelength measurements are made by interferometry in the visible, near-ultraviolet, and near-infrared regions. These measurements are transferred with lower accuracy to other spectral regions.

Industry need: Accurate secondary standards are required for calibration of spectroscopic instruments in many branches of science and technology.

Short-term objectives: Improvement of interferometric techniques; improvement of resolution in infrared and ultraviolet; use of new sources such as lasers.

ELECTRON BEAM CURRENT MEASUREMENT E.H.E. 8/12/64

NBS

FARADAY CUP (ACCURACY)

SECONDARY EMISSION MONITOR
(DESIRED ACCURACY)

SECONDARY EMISSION MONITOR
(PRECISION)

ACCURACY OR PRECISION
ONE PART IN
600
500
400
300
200
100

AVERAGE ELECTRON BEAM CURRENT, AMPERES
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3}

132
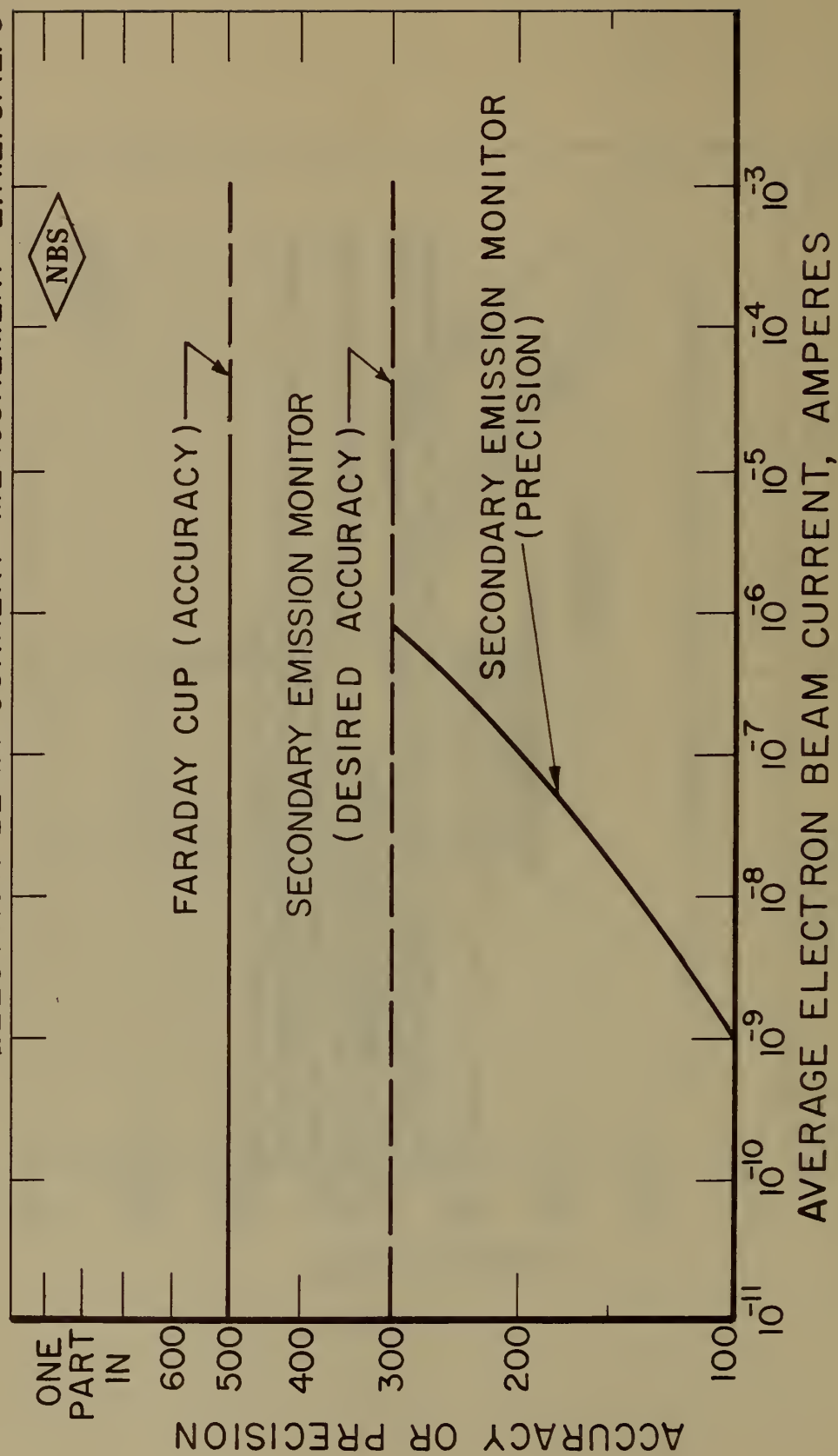
Electron Beam Current Measurement

J. E. LEISS, J. S. PRUITT, J. K. WHITTAKER, *Project Leaders*

The uncertainty shown on the chart applies to two techniques that are presently used at Stanford University and in French and German laboratories for measuring the current in the electron beam produced by an accelerator. The Faraday Cup is an absolute standard, but it completely intercepts and absorbs the beam; therefore, it is not a suitable device for monitoring the beam current during an experiment. The Secondary Emission Monitor (SEM) can be used as a monitoring device because the beam passes through essentially unaltered. Ranges are thus far limited to about 10^{-5} Å for the Faraday Cup and 10^{-6} Å for the SEM.

The SEM stability (precision) curve on the chart is an indication of the inconsistencies presently encountered in those laboratories already making measurements with this device. These inconsistencies presumably arise from effects that are associated with surface conditions of the foils used in the monitor. Many hours of exposure to the beam are frequently required before acceptable stability is achieved. It is necessary to determine the nature of such surface effects, so that plating or other techniques may be used in order to improve precision and obtain the desired accuracy without the necessity of calibration using a Faraday Cup.

At NBS, a Faraday Cup development program has been undertaken to develop a total absorption standard for the high-intensity beams up to 10^{-3} Å that will be obtained from the new NBS linear accelerator. This proves to be a difficult instrument to develop because of the very large amounts of energy that must be absorbed, at the same time maintaining adequate insulation resistance. A design has been developed and construction is under way. Investigations have been made, using the IBM 7094 computer, on the trapping of backscattered electrons, and magnetic field configurations have been developed that will trap the maximum number of electrons.

Studies of other types of intercepting and non-intercepting beam-monitoring systems have been made, including secondary emission and induction types, and prototype devices of each type are under construction at NBS.

It is also necessary that an accurate device which does not absorb the electron beam, such as the SEM, be developed in order to measure currents for the increasing applications of electron beams in radiation processing. Such efforts are a part of the electron current standards program of NBS.

133

NEUTRON EMISSION RATE: SOURCES OF KNOWN SPECTRA AND CONSTRUCTION

E.H.E. 8/12/64

NBS

1. CURRENT QUOTED UNCERTAINTY (HIGH-ENERGY SOURCES)
2. HIGH-ENERGY SOURCES } FUTURE EXPECTED
3. LOW-ENERGY SOURCES } NBS CAPABILITY

EMISSION RATE, Neutrons per Second

CALIBRATION UNCERTAINTY, One Part in
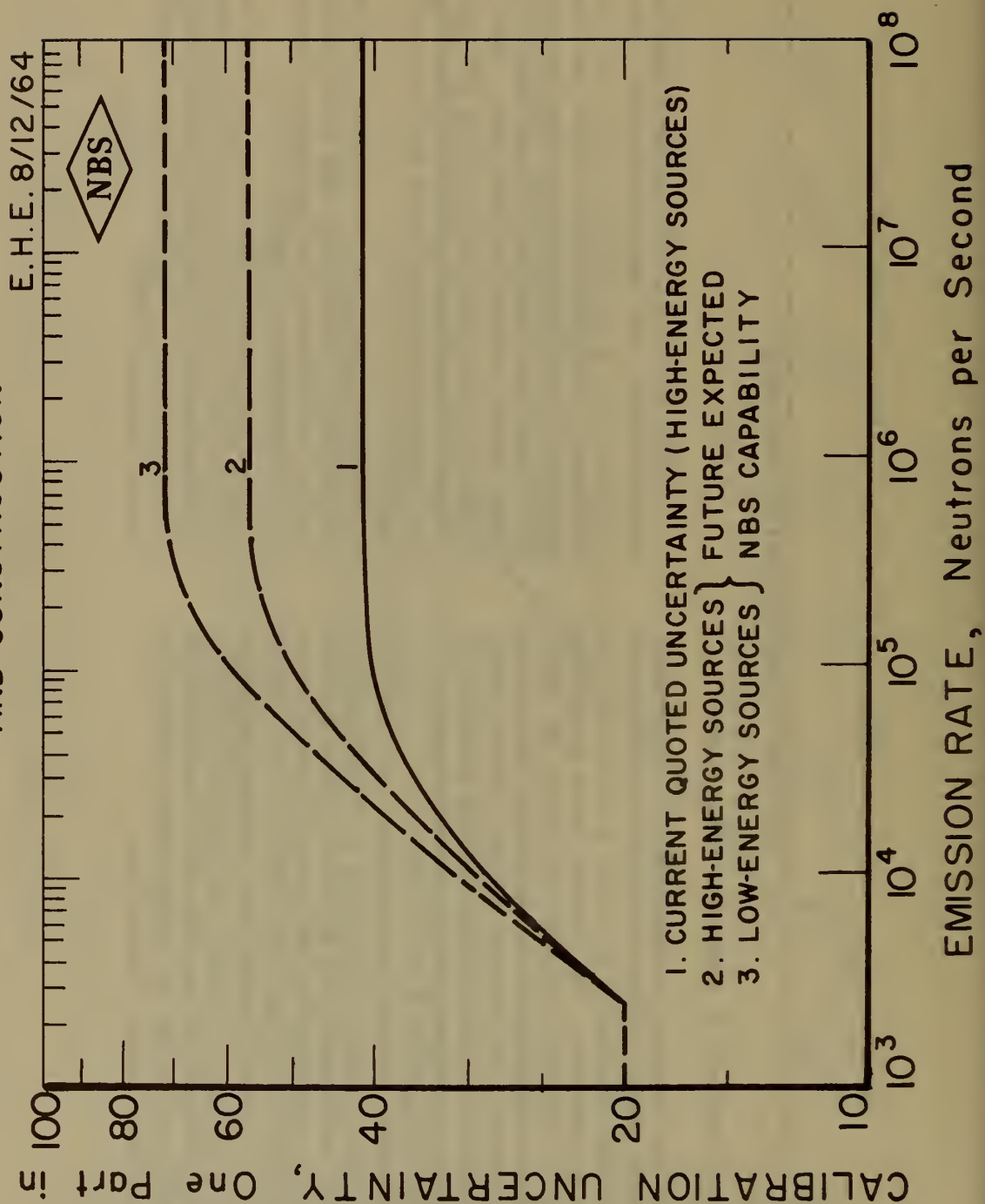
Neutron Emission Rate: Sources of Known Spectra and Construction

V. SPIEGEL, JR., *Project Leader*

Neutron sources calibrated by NBS are used as standards for fast neutron flux measurement, cross section measurements, fast neutron dosimetry, and to produce known thermal neutron fluxes in moderators. Present uncertainty in calibration of the neutron emission rate is ±2.5 percent, representing an estimate of systematic error. It would be highly desirable to decrease the uncertainty to approximately ±1 percent. Types of sources that are calibrated most frequently are Pu-Be (α,n) and Am-Be (α,n).

As indicated on the chart, calibrations are less accurate for source strengths below 10⁵ neutrons per second. The reason is that background radiation becomes a problem as source strength decreases. Among the principal sources of uncertainty in source calibrations are source and source holder capture of thermalized neutrons in the calibration bath. These effects have been investigated and minimized using thin teflon spheres of different sizes as source holders. These

have small thermal cross sections and reduce the thermal flux near the source by maintaining a moderator-free region around it.

The reason for the difference between the expected NBS future capability curves for high- and low-energy sources is that for low-energy sources no neutrons escape from the bath, while at high energy sources no neutrons escape and are therefore not detected. Measurements have been made of the thermal neutron flux in the source holder, and the absorption and fission cross sections of sources were calculated. These results make it possible to obtain more accurate corrections to apply to a standard known source. A new source holder with a low thermal neutron cross section has been made. New transistorized circuitry has resulted in improved counter stability.

In the near future, consideration will be given to a spherical bath with a higher concentration of manganese, and to a circulating bath that carries only a fraction of the liquid to the counter for sampling.

MEASUREMENT OF NEUTRON FLUX DENSITY

NBS E.H.E. 8/12/64

NEED BASED ON REQUIREMENT FOR PRECISION CROSS SECTIONS

PRESENT CAPABILITY

ONE PART IN

UNCERTAINTY

10^3

10^2

10

1.0

.01eV .1 1.0eV 10 100eV 1keV 10 100keV 1MeV 10 100 1BeV
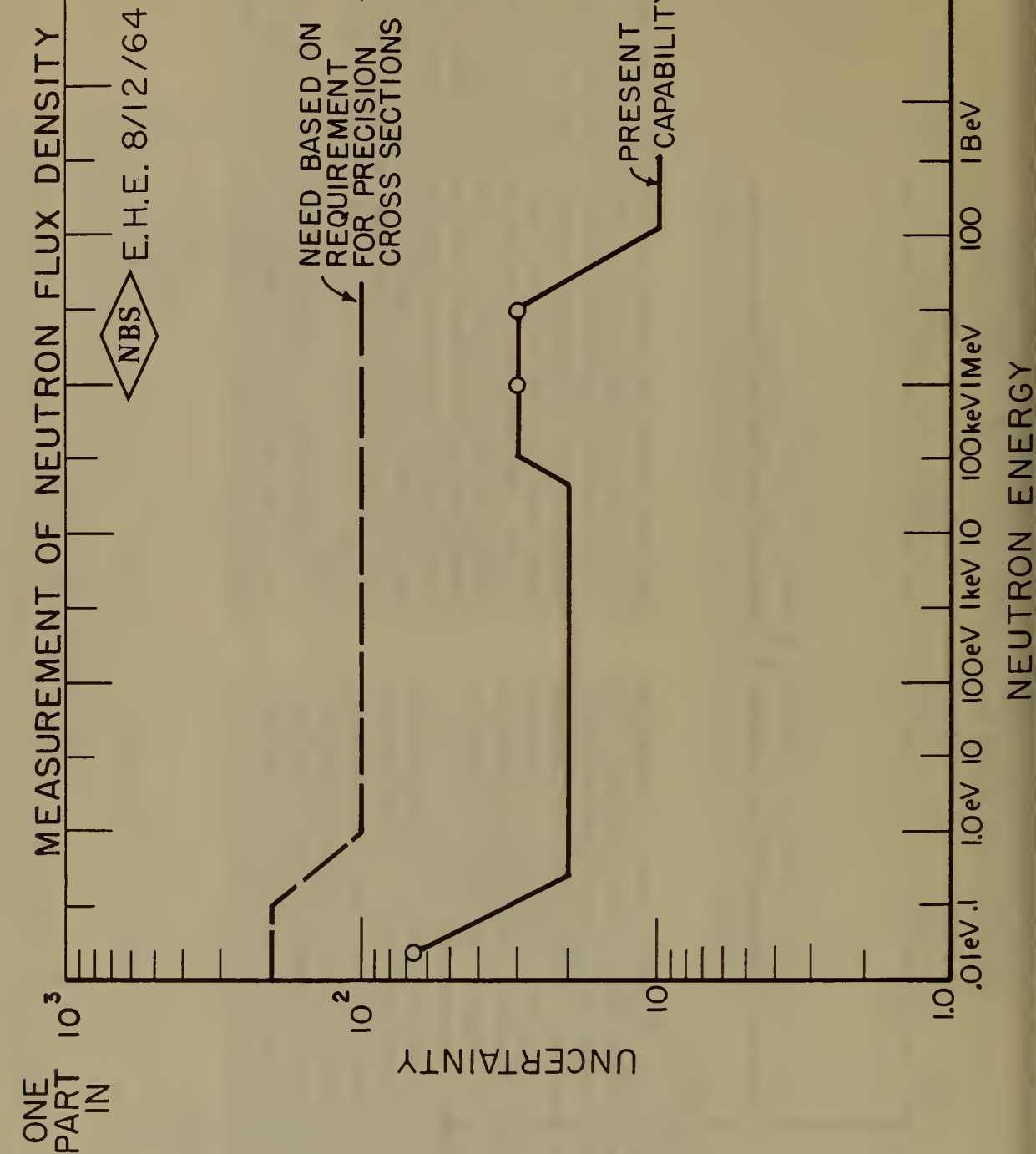
NEUTRON ENERGY

Neutron Flux Density

W. Murphey, *Project Leader*

Standard neutron fluxes are required over a wide range of energy from thermal neutrons to tens of MeV. The chart indicates the present uncertainty of measuring neutron flux density compared to the required accuracy, which is determined by the need for precision cross sections. In general, cross section requests can be satisfied with 1 percent accuracy, except at thermal neutron energies, where there exist requests for accuracy to within 0.5 percent in some of the fissionable nuclides. In addition, a standard of thermal neutron flux density is required for calibration of the thermal neutron flux density in power reactors and in research reactors located at universities and in national laboratories.

NBS has maintained for about 7 years a standard of thermal neutron flux density which has been absolutely calibrated twice by independent methods, and intercompared with several other laboratories. The uncertainty in the absolute calibration of this flux density is 1.5 percent—the sum of an estimated systematic error of 1 percent plus 1 standard deviation of 0.5 percent. National and international comparisons show agreement to within 1 standard deviation of 1.5 percent. A calibration service by activation of gold foils in the known flux is provided to the public on a routine basis.

When the NBS thermal neutron flux density was mapped recently using indium foils, it was found that there is greater spatial variation of the flux density than was previously believed to exist. An attempt is being made to measure the flux temperature in collaboration with laboratories in Canada and England.

138
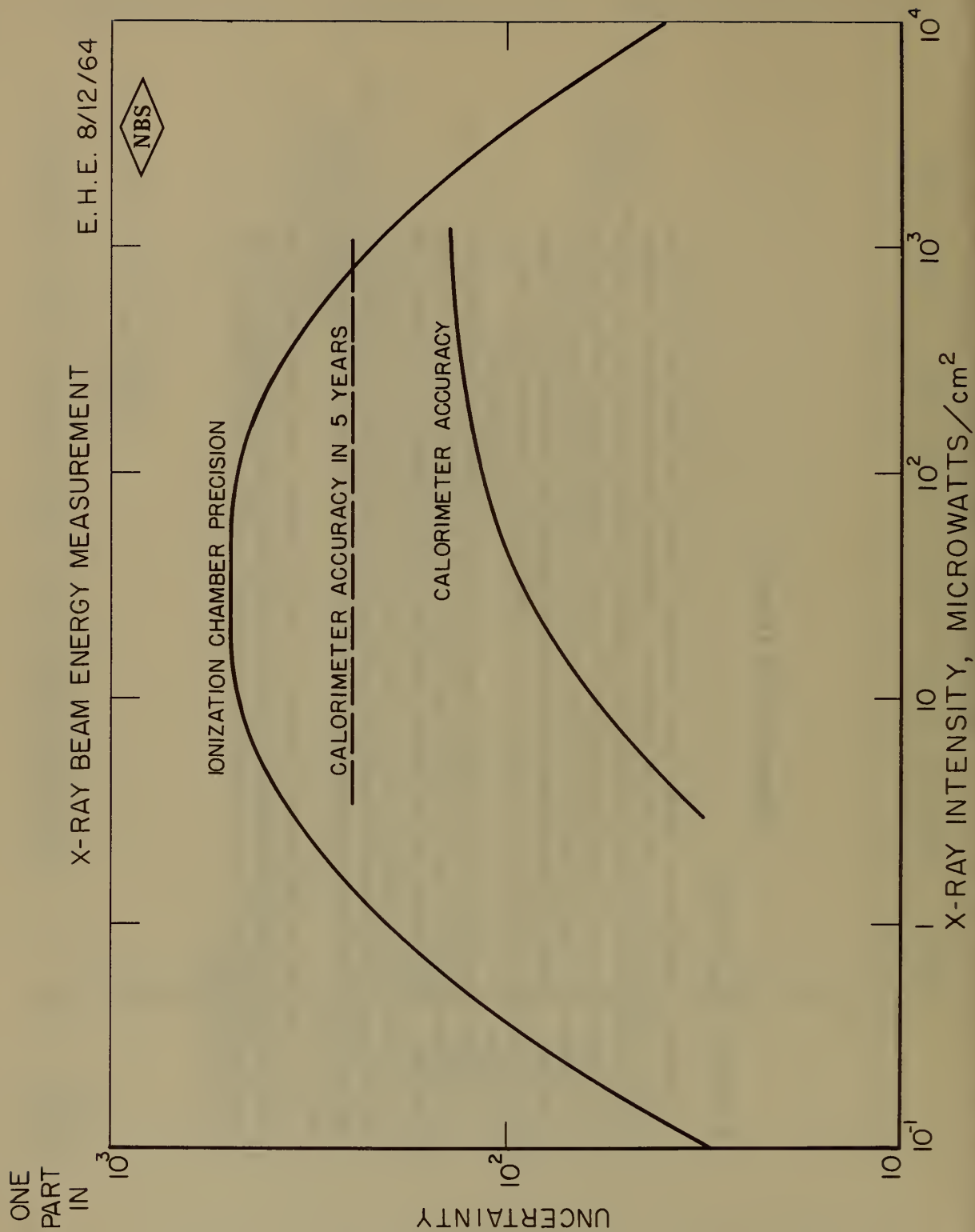
X-Ray Beam Energy Measurement

J. S. PRUITT, *Project Leader*

The chart shows the uncertainty in measurements of x-ray beam total energy (watt-seconds) in relation to x-ray intensity (μW/cm^2). Present calorimeter accuracy, with uncertainty based on estimated limits of systematic error plus 3 standard deviations, is the result of many years of effort to make absolute measurements of the total energy in x-ray beams. A basic limitation to such effort has been the low intensity of the available accelerators. When the NBS linear accelerator becomes operational, this limitation will be overcome, but problems such as intensity losses from the absorbing lead block will become more important.

Four standard ionization chambers have been designed and constructed at NBS for calibrating monitors used with the beam of a high-energy accelerator, within the range of 6 to 180 MeV. These chambers are available on loan to various laboratories for calibration of their accelerators. One of the chambers was carried to four European standards laboratories for comparison with similar chambers constructed there. The intercomparisons showed that it is possible to construct a replica which agrees with the standard NBS chamber to within a few tenths of 1 percent. The chart curve, with a least uncertainty of about 0.2 percent, concerns the reproducibility of measurements with a given ionization chamber.

As the use of high-energy x-ray beams for radiation processing and radiation therapy increases, the requirement for the accuracy of measurements also increases. Therefore, the present uncertainty in the calorimetric determination of total x-ray energy should be improved to approximately ±0.5 percent.

References:

J. S. Pruitt and S. R. Domen, Calorimetric calibration of an ionization chamber for determination of x-ray total beam energy, *J. Res. NBS 66A (Phys. and Chem.), No. 5, 371 (Sept.–Oct. 1962).*

J. S. Pruitt, A. Allisy, G. Joyet, W. Pohlit, M. Tubiana, and C. Zupancic, Transfer of NBS x-ray beam calibrations, *J. Res. NBS 66C (Eng. and Instr.), No. 2, 107 (Apr.–June 1962).*

X-RAY AND GAMMA-RAY EXPOSURE STANDARDS IN ROENTGENS   EHE 8/12/64

NBS

CAVITY CHAMBER

FREE AIR CHAMBER

—— PRESENT ACCURACY
—··— PRECISION
— — DESIRED ACCURACY

UNCERTAINTY-ONE PART IN

10^3

10^2

10

0.1 %
0.2 %
0.5 %
1.0 %
2.0 %
5.0 %
10 %

10   20   40 60 80 100   500   1000   10,000

EFFECTIVE PHOTON ENERGY, keV
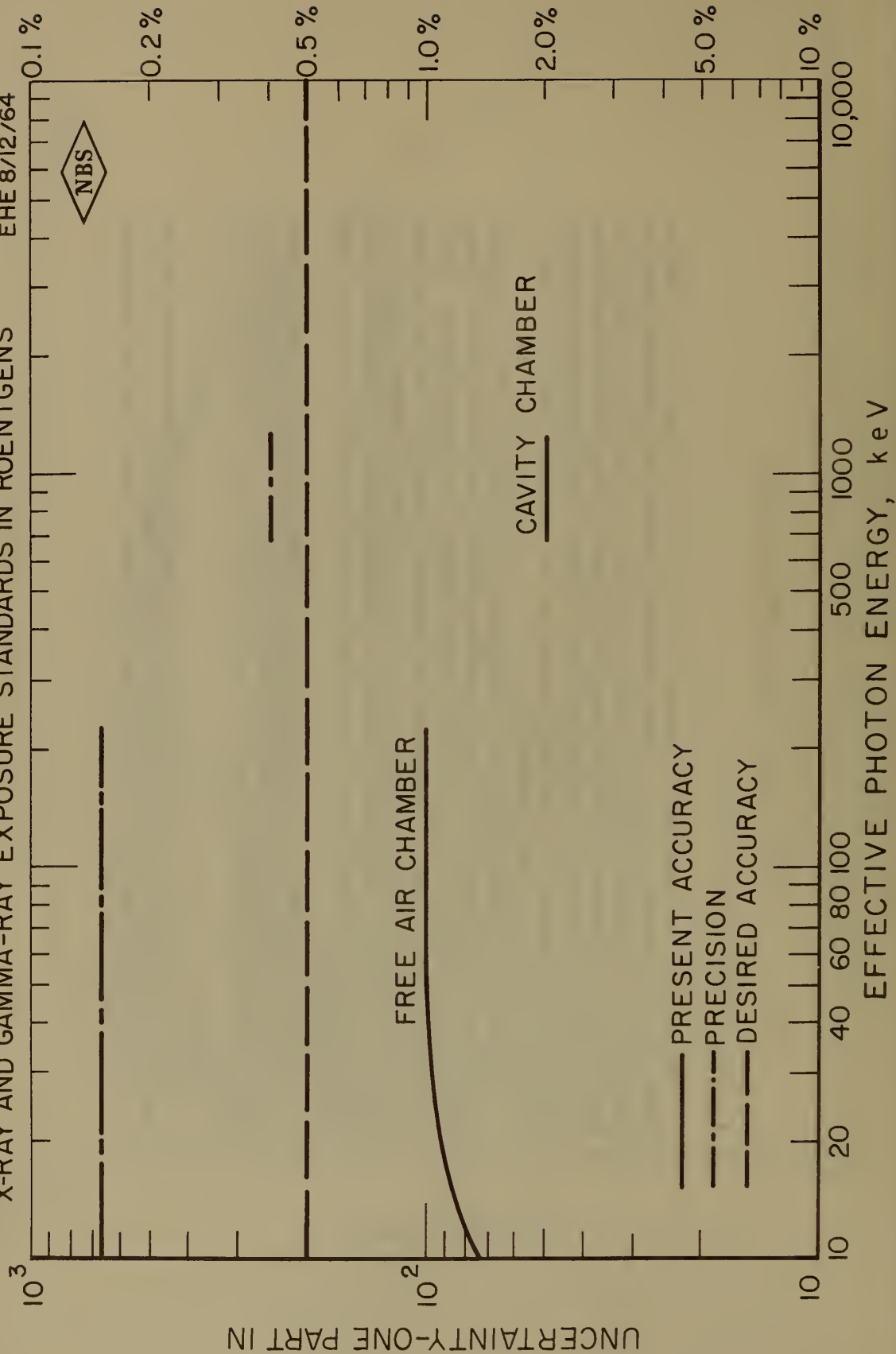
X-Ray and Gamma-Ray Exposure Standards

H. O. WYCKOFF, *Section Chief*

NBS calibrates x- and gamma-ray exposure instruments in roentgens (R). These calibrations are performed by a substitution method with the national standards for x rays up to 250 kV. The national exposure standards are free-air chambers. Three are used to cover the range from 10 to 250 kV. Current estimates of the International Commission on Radiological Units and Measurements (ICRU) indicate that maximum uncertainty in the determinations with the free-air chamber is about 1 percent for 60- to 300-kV x-rays (effective energies of about 30 to 210 keV). NBS estimates that this uncertainty may be as high as 1.3 percent at 10 keV, with a systematic error of about 1 percent and a reproducibility of 0.1 or 0.2 percent, based on 1 standard deviation.

Cavity ionization chambers are the national exposure standards for measurement of cobalt 60 and cesium 137 gamma rays. It is estimated that the maximum uncertainty of determination of exposure with such instruments is about 2 percent, including 1.6 percent systematic error and 0.4 percent reproducibility, based on 1 standard deviation. High priority at NBS is being given toward reducing this uncertainty. The chart indicates the present accuracy of the national standards, as well as the precision with which measurements can be made with them.

Several direct comparisons of 60- to 250-kV x-ray standards of different national laboratories have been completed during the past decade. Generally, the agreement has been within 0.5 percent. Additional comparisons under the auspices of the International Bureau of Weights and Measures are contemplated for the fall of 1965. No direct comparisons of national exposure standards for gamma rays have been reported.

One of the reasons that additional direct international comparisons have not been undertaken is that the equipment which must be transported is heavy and somewhat delicate. To facilitate such comparisons, NBS has transfer instruments under development. Preliminary tests with such instruments indicate that indirect comparison with them can be nearly as precise as a direct comparison with the standards themselves.

These national standards are used for the calibration of transfer instruments or laboratory standards for the various laboratories and clinics that use radiation. The ICRU has recommended that x-ray machines used for therapeutic treatment be calibrated every one or two weeks and that the accuracy of the calibration of clinical instruments should be within 2 percent for the particular radiation qualities of interest. A calibration of clinical instruments is usually two steps removed from the national standards. The instruments at present commercially available have rather poor precision (generally not better than 1 percent), and the national standards have an inaccuracy of 1 or 2 percent. It is therefore desirable to improve the accuracy of the clinical standards and/or the accuracy of the national standards. An accuracy of 0.5 percent for the national standards seems desirable. The NBS transfer instruments that are now used for international comparison are a step in the direction of improving clinical standards; work to improve the national standards continues.

RELATIVE SPECTRAL DISTRIBUTION OF X-RAYS
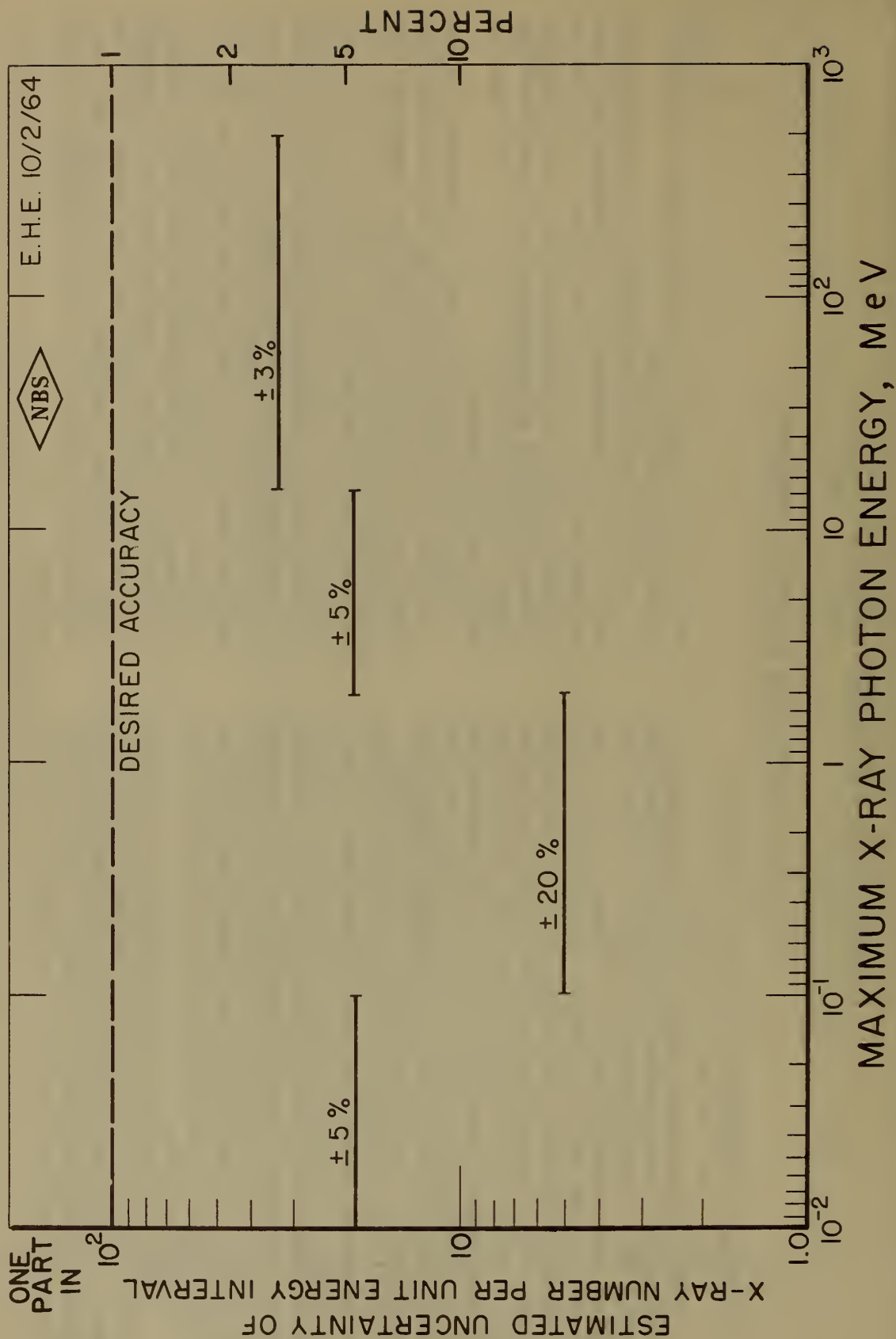
X-Ray Spectral Distribution

H. W. KOCH, J. W. MOTZ, R. C. PLACIOUS, *Project Leaders*

The spectral distribution of the x rays produced by a machine is fundamentally important to the increasing applications of these machines in medicine, radiography, and radiation processing of foodstuffs and other materials. Since the response of energy-dependent x-ray detectors depends upon the spectrum of the radiation being measured, it is essential that this spectrum be known accurately.

The probability and the polarization characteristics for x-ray production depend on target material, target thickness, and the kinetic energy of the impinging electron beam. Present calculations of x-ray production are based on the Born approximation; for the medium electron energy range (100 keV to 5 MeV) they are known to be in error, but this is the range of greatest practical interest and application. For this reason, NBS has pioneered in experimental determinations. The x rays used in these experiments are produced in thin targets so that the producing electron direction and energy are known. The chart shows uncertainty of the relative spectral distribution, either calculated or observed, and is an estimate of systematic error, the statistical errors being negligible in comparison.

As a logical extension of this effort, NBS now has under investigation the spectral distribution as the target thickness is increased. Additionally, some data have been obtained on both bremsstrahlung x-ray production and characteristic x-ray production for thin and thick targets, for electrons in the low-energy region from 50 to 500 keV.

Completion and publication are planned for the experimental and theoretical work on x-ray production with thin and thick targets for electron energies of 50 to 100 keV. Measurements will be made of the bremsstrahlung tail associated with electron elastic scattering, with comparisons between the experimental results and various theoretical predictions.

VIII.   Index

145